Volume 27 JUNE, 1957 Number 2

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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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The American Association of Petroleum Geologists

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Among papers to appear in forthcoming issues of the *Journal* are the following:

Structural petrology of the Pico Anticline, Los Angeles County, California. By Lawrence C. Bonham.

Observations on limestones. By Frank J. Moretti.

Authigenic brookite in Cretaceous Gallup Sandstone, Gallup, New Mexico. By Ming-Shan Sun and John Eliot Allen.

Pennsylvanian sandstones of the Eastern Interior Coal Basin. By Raymond Siever.

Surficial sediment in Lake Mead. By B. N. Rolfe.

Authigenic montmorillonoid cement in andesitic sandstones of central California. By J. F. Lerbekmo.

Three-dimensional shape analysis of fine-grained sediments. By Alan E. Wright.

Tracing turbidity current deposits down the slope of an alpine basin. By Albert Carozzi.

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Clay minerals from the Ventura Basin, California. By William Quaide.

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Comparison of percentage and ratio data in facies mapping. By W. C. Krumbein.

Hydrothermal alteration of Phosphoria mudstones. By Lawrence F. Rooney.

The Petrology of the Whita Sandstone, southern Scotland. By A. E. M. Nairn.

Cyclic patterns in mechanically deposited Pennsylvanian limestones of northeastern Nevada. By R. H. Dott, Jr.

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

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FIGS. 1–16, JUNE, 1957

SEDIMENTS OF THREE BAYS OF BAJA CALIFORNIA: SEBASTIAN VISCAINO, SAN CRISTOBAL, AND TODOS SANTOS[1]

K. O. EMERY, D. S. GORSLINE, E. UCHUPI, AND R. D. TERRY
University of Southern California, Los Angeles, California

ABSTRACT

Study of more than 1350 sediment samples from three bays facing the Pacific coast of Baja California shows that the sediments are closely related to oceanographic conditions. At Sebastian Viscaino Bay the sediments are coarsest and of highest calcium carbonate content in a strait that is swept by tidal currents. Adjoining bands of progressively finer sediment result from lower velocities of the water at both ends of the strait. At one end of San Cristobal Bay the sediments are coarse and of high calcium carbonate content owing probably to local upwelling of water. The rest of the bay is an area of slow deposition of detrital sediments and thus it contains the authigenic minerals glauconite and phosphorite. The third bay, Todos Santos, is largely closed off from the open sea by protecting islands; accordingly, its sediments show a decrease in grain size from shore to deep water. Sediments of the same grain size in the different bays do not necessarily have the same percentage of calcium carbonate or of organic matter because of the different environmental controls. Such present-day background knowledge is useful in interpreting ancient sediments with respect to depositional environments.

INTRODUCTION

The statement, "The present is the key to the past," holds special significance for sedimentologists. Ancient sedimentary rocks can yield information on original water temperature, salinity, oxygen and nutrient content, and currents only if the surviving characteristics of the sediment and its content of fossils are interpreted in the light of known relationships between modern sediments and their environments. Success in interpretation of ancient sedimentary rocks thus requires the accumulation of a large fund of information about modern sediments and environments.

During World War II, a program of measuring the control on underwater acoustics exerted by various water conditions and bottom sediments was pursued at the University of California Division of War Research (Russell, 1950). In order to encompass a wide range of environments, measurements were made in many areas off California and Mexico. Much of the information presented in this report is a by-product of the acoustic work. The principal Mexican areas for which samples and other data are available are Sebastian Viscaino, San Cristobal, and Todos Santos Bays (fig. 1). Each bay is a relatively wide part of the narrow continental shelf, and each has a different degree of exposure to the open sea that has produced differences in their sediments.

Nearly all of the samples were collected by Emery and Dr. F. P. Shepard using underway samplers and less commonly snappers and dredges. Some dredge and snapper samples from the bays were also made available from the files of Allan Hancock Foundation. About 20 percent of these samples were screened and pipetted; the texture of the remainder was estimated by a comparison coding method developed by Emery and Gould (1948). Additional data for Sebastian Viscaino Bay were collected in 1953 by Gorsline as a member of a Scripps Institution of Oceanography expedition. These data were combined with the earlier material as a master's thesis at the University of Southern California. Samples from Todos Santos Bay were studied by Uchupi and those from San Cristobal Bay by Terry in the sediment laboratory of the Allan Hancock Foundation, University of Southern California.

CLIMATE AND GEOLOGICAL SETTING

The climate in the region is arid, with an average rainfall at Cedros Island of only 3.5 cm annually during the three-year period 1944 to 1946 (Osario-Tafall, 1948). Farther north near San Diego the average annual precipitation is nearly ten times greater. In both areas most of the rain occurs during winter months. Wind along the entire coast

[1] Contribution of Allan Hancock Foundation No. 171.

is mostly of diurnal nature with a gentle land breeze at night and a stronger (5 to 10 m/sec) northwesterly wind blowing from the sea at day.

Coastal surface water temperatures range mostly between 13 and 21° C, but local variations resulting from upwelling may be as great as the seasonal range (McEwen, 1916; Hubbs, 1948). The surface salinity exhibits only a small range of between 33 and 34 °/₀₀ (parts per thousand) because there is little seasonal dilution by runoff.

The geological structure of Baja California is dominated by a westwardly tilted fault block composed of quartz diorite, granodiorite, schist, and gneiss. The fault block forms a mountain range that reaches elevations of between 1500 and 3000 m along much of the length of the peninsula and, thus, is referred to as the Peninsular Range.

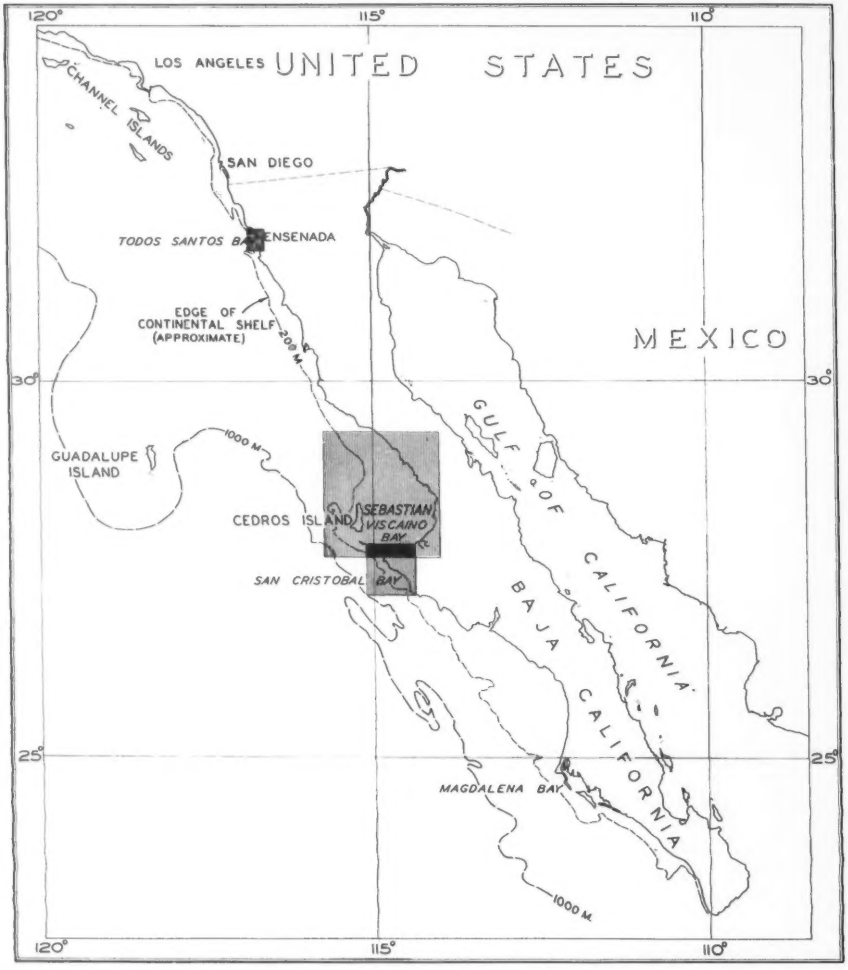

FIG. 1.—Locations of the three Mexican bays for which sediments were studied.

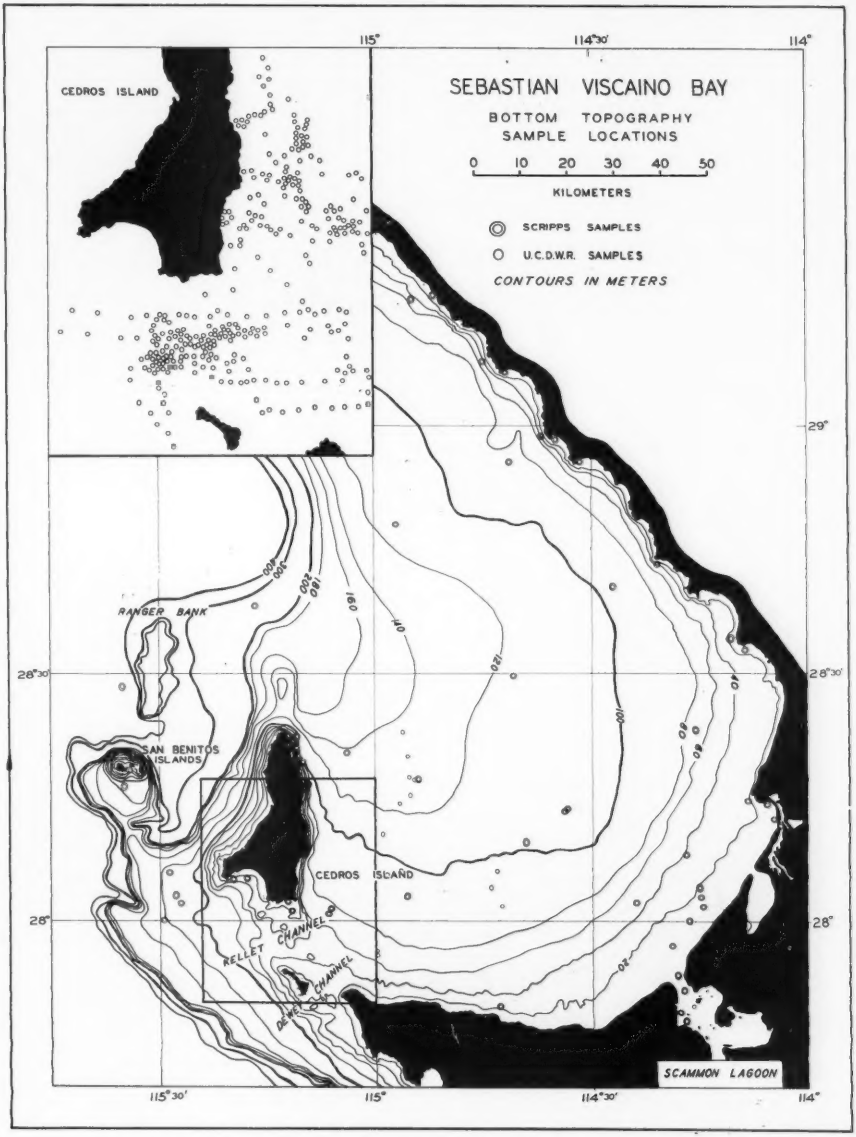

FIG. 2.—Contour map of Sebastian Viscaino Bay with contours in meters. Circles show positions of bottom samples.

A parallel but much shorter and lower (1000 m) range on the small peninsula southwest of Sebastian Viscaino Bay extends northwestwardly through Cedros Island and Ranger Bank. Between the two mountain ranges is the broad low Santa Clara Desert, consisting of Quaternary alluvium and dunes. All three bays of this study are bordered by ancient crystalline rocks, Quaternary sediments, and Tertiary strata consisting chiefly of sandstones with some conglomerates, silts, tuffs, and lavas (Beal, 1948).

SEBASTIAN VISCAINO BAY

Soundings from U. S. Hydrographic Office chart 1193 and from fathograms made during sampling operations served as the basis for the contour map of Sebastian Viscaino Bay (fig. 2). The contours show that the central part of the bay is a wide slightly concave surface having an average slope of 0°07′. This area is an extension of the Santa Clara Desert, which was itself once covered by the sea, as shown by marine terraces and by botanical evidence that favors an ancient separation of Sierra Viscaino from the Peninsular Range (Gentry, 1950). The presence of several broad shallow lagoons fringing the present shore suggests that the plain has been formed largely by repeated filling of lagoons behind beaches. Beaches also extend along most of the mainland except for the cliffed shores of the northern part of the bay and of the peninsula south of Cedros Island.

Forming the southwestern boundary of the bay are the mountainous Cedros Island and the small Natividad Island. These islands are separated from each other and from the mainland by Kellet and Dewey Channels. Kellet Channel is the wider (15 km) and the deeper (45 m) and it contains a 20-m submarine terrace extending southward from Cedros Island. West of this island near the shelf break are San Benitos Islands (Hanna, 1927) and Ranger Bank (Emery, 1948). North of Ranger Bank the shelf break terminates the central flat area of Sebastian Viscaino Bay at depths between 160 and 180 m. Seaward of the shelf break the continental slope descends to depths greater than 4000 m (Shepard, 1950).

Texture

The texture of the sediments is based upon 83 screen and pipette analyses and about 450 by code estimation. The analyses, plotted in map form (fig. 3), show a clear subdivision of the sediments into the following units: dunes, beaches, nearshore areas, central bay, and straits. A summary of the grain-size distribution in each subdivision is given by representative cumulative curves in figure 4. Dunes, present only on the mainland, consist of finer grained and better sorted sand than the beaches from which they are derived. The beaches along the mainland are finer grained and better sorted than those on the leeward side of Cedros Island because of their lower content of shell fragments and their greater exposure to wave action. Nearshore sediments form a belt about 5 km wide as a transition zone between the sediments of the beaches and those of the central bay. Within the central bay the sediments present a gradual decrease in grain size outward to the shelf break. In the strait south of Cedros Island, the strong tidal current has winnowed away or prevented the deposition of fine-grained sediments, leaving bedrock exposed or locally covered by patches of coarse shell and algal sediment.

Calcium Carbonate

Calcium carbonate was determined by weight loss after treatment of the whole sample with dilute hydrochloric acid, the same method that was used in the other two bays. At Sebastian Viscaino Bay, calcium carbonate probably is entirely derived from shell fragments (pelecypods and gastropods), calcareous red algae, and foraminifers. Shell fragments and algal debris dominate in the strait area, where they comprise up to 100 percent of individual samples and average about 60 percent (fig. 5). The typical large size of the fragments of organic debris makes the strait sediment the coarsest of the entire bay and one of the coarsest kinds of sediment on the sea floor of the Pacific coast (Emery, 1954).

Shell fragments are the chief form of calcium carbonate in beach and dune sands. In the beach sands of Cedros Island the shells locally give rise to irregular cumula-

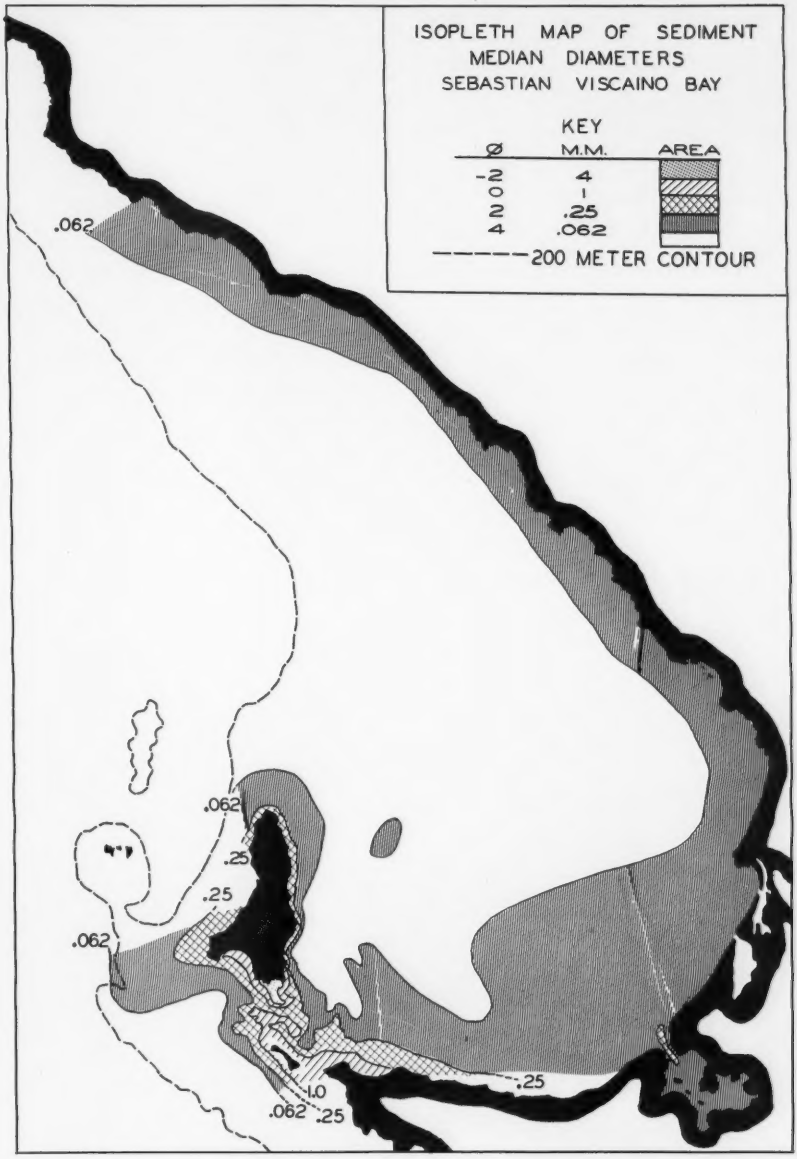

FIG. 3.—Distribution of median diameters of sediments in Sebastian Viscaino Bay. Based on 533 samples, mostly concentrated in the strait south of Cedros Island.

tive grain-size curves (fig. 4A-curve 1), indicating double modes in size frequency. Many shell fragments are also present in the nearshore sediments, and near the entrance to Scammon Lagoon the shells are clearly derived from a large local population of *Donax*, a small pelecypod. Shell fragments also occur in the marginal portions of the central bay and in an area of strong currents north of Cedros Island. Elsewhere, in the finer sediments of the central bay, foraminiferal tests rather than shells serve as the chief source of calcium carbonate.

Organic Matter

The amount of organic matter in the sediments was determined by the loss in weight during treatment with hydrogen peroxide. Although the method is not precise, it is satisfactory in a relative sense.

Organic matter probably reaches its highest values in the tidal flats and shallows of Scammon Lagoon, but no samples are available. In the open bay, organic matter constitutes slightly more than 5 percent of the total dry sample in two separate areas (fig. 6). The larger area occupies the broad con-

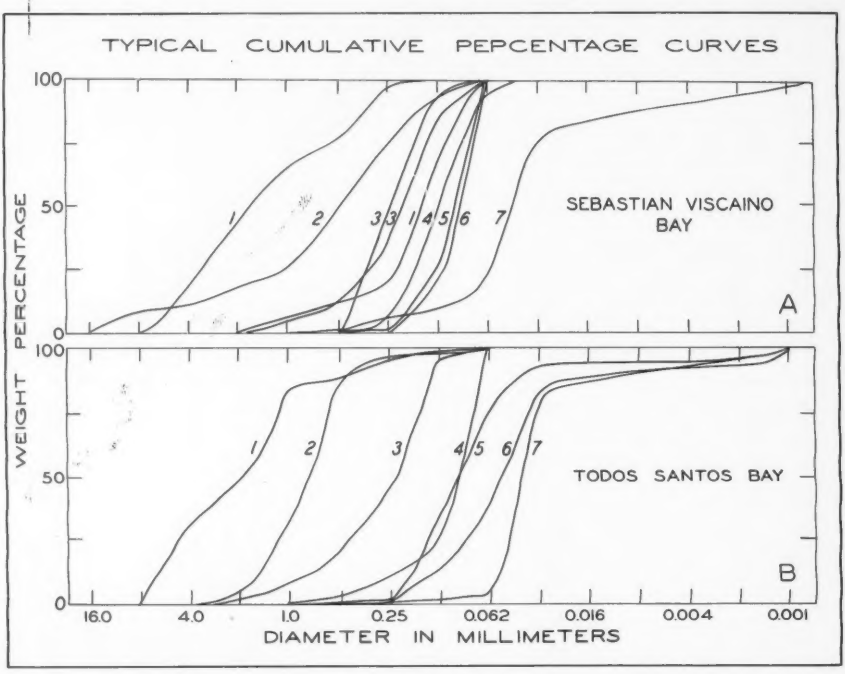

FIG. 4A.—Typical cumulative curves of grain size for sediments of Sebastian Viscaino Bay in:
1. Cedros Island beaches (17% $CaCO_3$, <1% org. m.)
2. Strait (62% $CaCO_3$, 0.4% org. m.)
3. Nearshore off Cedros Island (11% $CaCO_3$, 1.9% org. m.)
4. Mainland beaches (11% $CaCO_3$, <1% org. m.)
5. Dunes (6% $CaCO_3$, <1% org. m.)
6. Nearshore off mainland (7% $CaCO_3$, 0.8% org. m.)
7. Central Bay (23% $CaCO_3$, 3.4% org. m.)

B.—Typical cumulative curves of grain size for sediments of Todos Santos Bay in:
1, 2. Ridge (53% $CaCO_3$, 0.35% org. m.)
3, 4. Nearshore (9% $CaCO_3$, 0.5% org. m.)
5, 6. Outer part of shelf (16% $CaCO_3$, 1.4% org. m.)
7. Trough (16% $CaCO_3$, 3.9% org. m.)

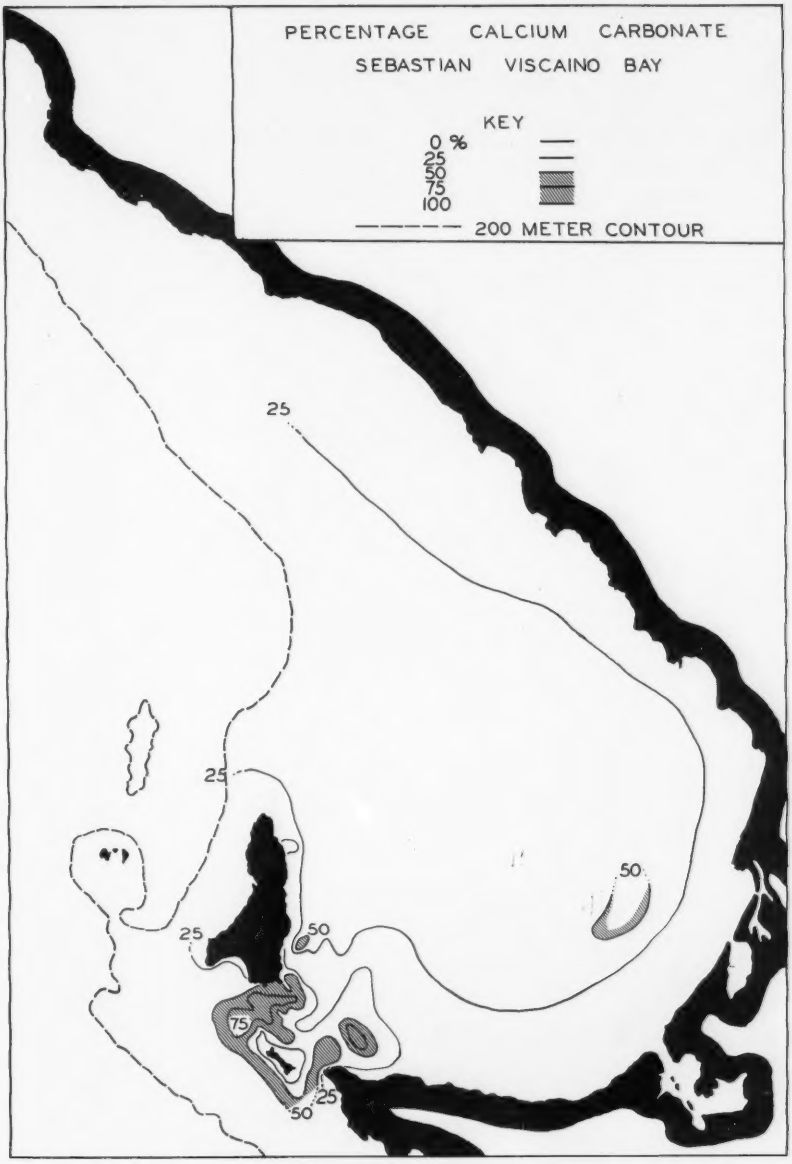

FIG. 5.—Distribution of percentage calcium carbonate in sediments of Sebastian Viscaino Bay. Based on acid-soluble fractions of 216 samples.

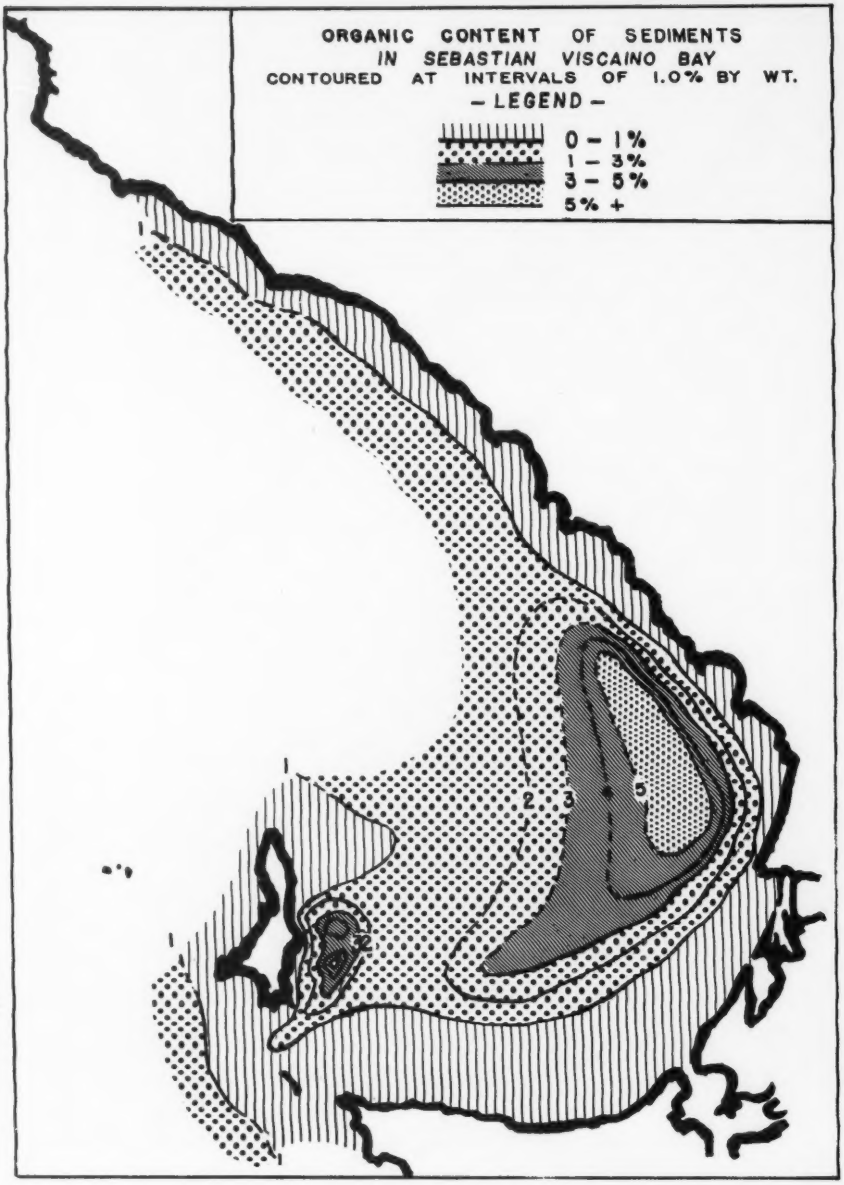

FIG. 6.—Distribution of percentage total organic matter in sediments of Sebastian Viscaino Bay. Based on weight loss of 32 samples by treatment with hydrogen peroxide.

vexity in the eastern half of the bay to which currents carry it from a zone of upwelling along the northern coast. The smaller area of sediments rich in organic matter is on the lee side of Cedros Island, to which it is swept from the area of prolific algal growth in the straits.

Other Characteristics

Thirty-six of the insoluble residues left from acid treatment were separated into light and heavy mineral fractions using acetylene tetrabromide as the heavy liquid. A high concentration of more than 10 percent heavy minerals occurs in the detrital sands of the mainland beaches and mainland nearshore areas. Marginal parts of the central bay and the beaches and nearshore areas of Cedros Island have heavy mineral contents of 5 to 10 percent, whereas most of the central bay has less than 5 percent. The seaward decrease of heavy minerals is a normal response to a decrease in grain size; heavy minerals are usually less common in clays and fine silts than in coarse silts and fine sands, as shown by Emery, Butcher, Gould, and Shepard (1952) in samples from off San Diego, California. Among the heavy minerals, hornblende is dominant, comprising about half the total number of grains. Biotite, epidote, and zircon are next in order of decreasing abundance. The remainder are characterized by resistates such as magnetite, leucoxene, garnet, sphene, and topaz. The light minerals are almost exclusively quartz and plagioclase with quartz slightly the more abundant.

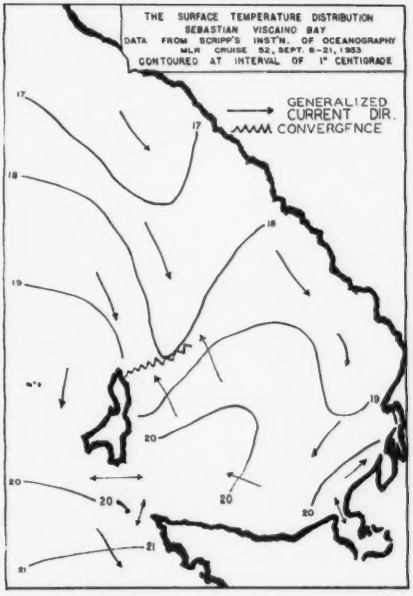

FIG. 7.—Surface currents in Sebastian Viscaino Bay. Lines show surface water temperture (°C) for September, 1953. Arrows show current directions measured by geomagnetic electrokinetograph. These data agree well with the earlier data of Dawson (1952).

Relationship to Water Movements

Waves and swells of Sebastian Viscaino Bay are chiefly from the northwest. They produce a southward shore drift of sand which must then accumulate at the head of the bay and form the beaches of well-sorted sands that partly close off the lagoons from the bay. Protection by Cedros Island and the lack of a more or less continuous contribution of sediment by longshore drift accounts for the presence on the island's southeastern side of small beaches composed of poorly-sorted shell sand of local origin.

The northwesterly winds of the region produce some upwelling near the northern end of the bay, as indicated by low temperatures of surface waters in that area. The positions of isotherms in figure 7 show that this cool water flows around the bay in a clockwise pattern (Dawson, 1952), transporting sediments along the mainland shore in the same direction as does the wave drift. During the summer, water from the shallow lagoons at the south end of the bay forms a mass of warm water that flows northward along the eastern side of Cedros Island to complete the clockwise circulation pattern of surface waters.

The water movement that is most interesting and important with respect to the distribution of sediments is a tidal flow of water in and out of the two straits south of Cedros Island. Currents of more than 4 km per hour have been measured. These are capable of sweeping away fine sediment and leaving bare rock in the narrowest part of the strait. The rock is bordered by a band of coarse shell gravel, and this in turn by

bands of progressively finer sediment. Much of the water that leaves the bay during ebbing tide is warm water contributed by the lagoons. The water that enters the bay from the open sea during flooding tide, however, is cold and clear (Secchi disk reading of 15 m) and probably contains fairly high contents of plant nutrients owing to turbulent mixing. This could account for the wide area of calcareous red algae in the strait.

SAN CRISTOBAL BAY

Fathograms and the spot soundings on U. S. Hydrographic Office chart 1310 served for drawing the contours of figure 8. The shore is cliffed and consists of a series of 5 arcs separated by slightly projecting points. The smallest arc, Turtle Bay, is nearly landlocked, whereas the largest one, San Cristobal Bay, is a broad open area between the shore and the shelf break at about 120 m depth. There are no protecting islands, no perennial streams, and few beaches in the entire area of figure 8. The topography of the shelf is different from that at Sebastian Viscaino Bay, with numerous small irregularities only a few meters shallower than their surroundings (Emery and Champion,

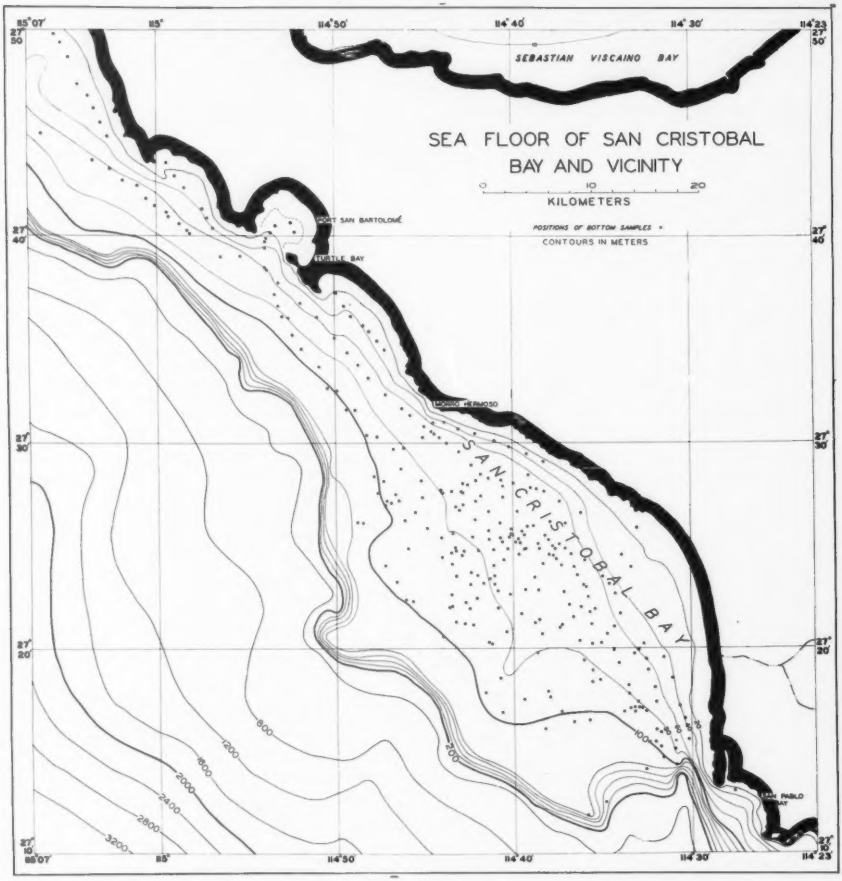

FIG. 8.—Contour map of San Cristobal Bay and vicinity with contours in meters. Dots show positions of bottom samples.

1948, plate 2), termed shelf knolls. Sampling showed that these consist mostly of rock projecting through a blanket of sediment.

Texture

Texture of sediments was based on 53 screen and pipette analyses plus 230 analyses estimated by code. The resulting median diameters show the sediment to be of a smaller range in grain size than that at Sebastian Viscaino Bay (0.03 to 1.0 mm versus 0.03 to 4.0 mm), and it is less well arranged into areas of differing texture. The coarsest sediment occurs in three small areas in the central and northern parts of San Cristobal Bay (fig. 9-A). Local irregularities in grain size are the result of sampling near the small rocky shelf knolls that project above the sand.

Calcium Carbonate

In addition to acid treatment, calcium carbonate in San Cristobal Bay and vicinity was estimated visually according to the apparent bulk of shell fragments and foraminiferal tests. Comparison of the two methods shows a rather wide spread of points—an average difference of about 12 percent. It is notable that for samples which are low in calcareous remains, the visual estimate was was low—suggesting the presence of calcium carbonate of silt and clay size that would

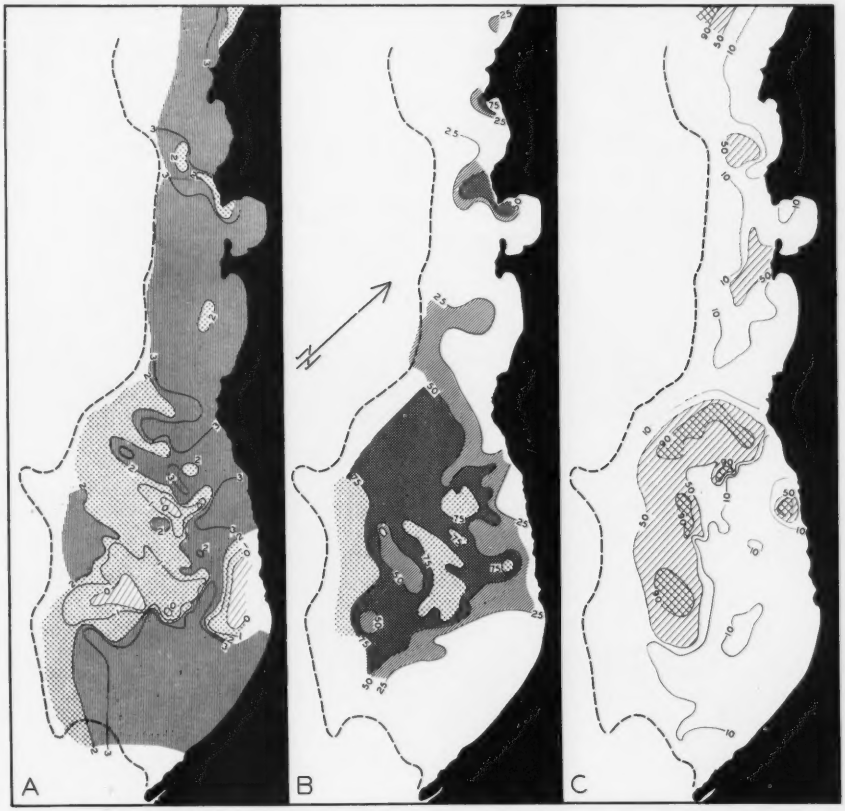

FIG. 9.—Some characteristics of sediments in San Cristobal Bay: A. Distribution of median diameters (phi units) of sediments in 283 samples. B. Distribution of percentage calcium carbonate in 206 samples. C. Percentage of organic debris that consists of foraminiferal tests. Nearly all the rest of the organic debris is shell fragments.

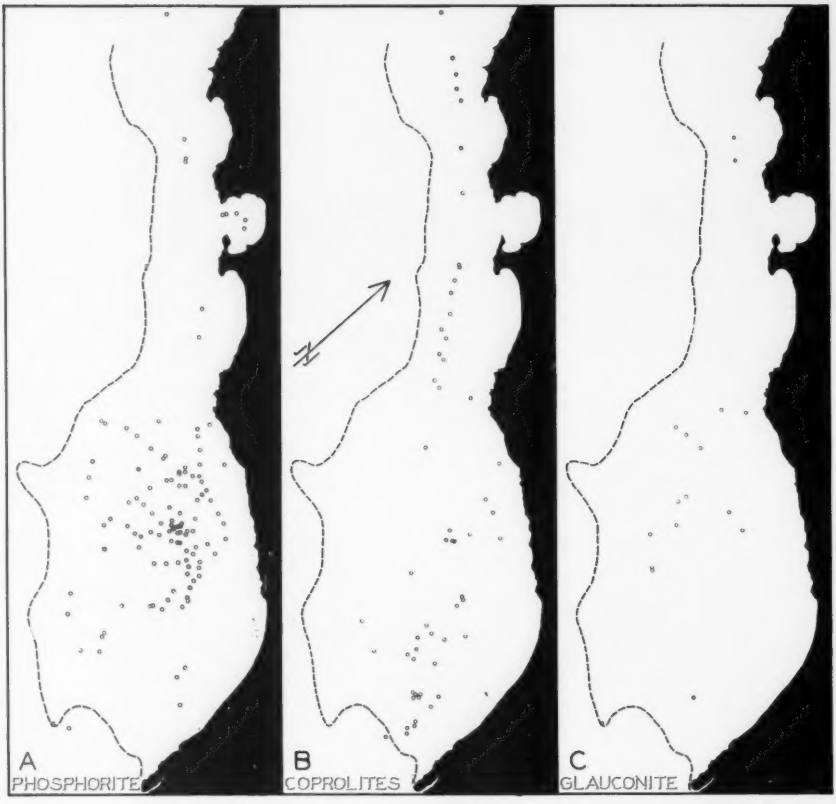

FIG. 10.—Positions of samples containing authigenic minerals at San Cristobal Bay.

easily be overlooked. For samples containing abundant calcareous remains, the visual estimate tended to be high, perhaps indicating partial filling of shells and tests by detrital silts and clays.

According to the chemical determinations, calcium carbonate averages about 50 percent throughout the area, with higher percentages occurring immediately south of the two northern points and in a large area in the northern half of San Cristobal Bay (fig. 9-B). A plot of the percentage of foraminiferal tests in the calcium carbonate fraction (consisting only of foraminifers and shell fragments) shows that shells dominate in most of the bay but that foraminiferal tests dominate in the seaward half of the area that contains the highest percentage of total calcium carbonate (fig. 9-C).

Organic Matter

Organic carbon was determined on 16 samples using Allison's (1935) potassium dichromate reduction method and converted to total organic matter by multiplying by the factor 1.7. The results show a range of organic matter from 0.6 to 2.0 percent and an average of 1.3 percent. These values are similar to those of the nearshore zone of Sebastian Viscaino Bay but are much lower than those of the fine muds in the central part of that bay.

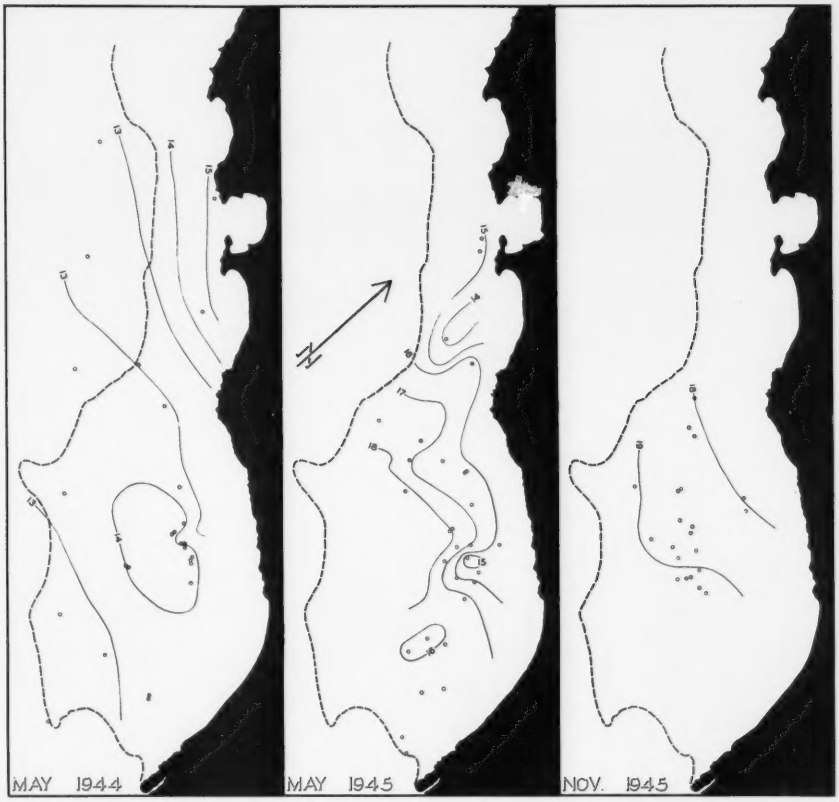

FIG. 11.—Distribution of surface water temperatures (°C) in San Cristobal Bay during three separate brief surveys. Note the general presence of colder water in the northern half of the bay.

Other Characteristics

Samples from San Cristobal Bay and vicinity contain authigenic minerals that are rare or absent in the other two bays. Most abundant of these is phosphorite. Few samples contain more than a few percent of phosphorite, but this material is widespread throughout the area (fig. 10-A). Glauconite is commonly associated with the phosphorite but is less widely distributed (fig. 10-C). Both phosphorite and glauconite are typical of areas of the sea floor that are rarely reached by coarse detrital sediments and are by-passed by fine detrital sediments. Many samples also contain ovoid pellets mostly 0.5 to 2 mm long and composed of slightly cemented fine sand, silt, and clay. These are probably worm castings, but are termed only coprolites in figure 10-B. Possibly related to the coprolites are irregular masses of authigenic pyrite, some of which have shapes that suggest replacement of organic debris.

Many of the detrital grains which are present in San Cristobal Bay have become highly weathered, owing to the same slow rate of deposition that permits the growth of authigenic minerals. Those detrital minerals that are identifiable show the assemblage to be similar to that of Sebastian Viscaino Bay; quartz, feldspar, hornblende, epidote, bio-

tite, enstatite, magnetite, sphene, and garnet.

Relationship to Upwelling

San Cristobal Bay, unlike the other two bays of this study is almost completely exposed to the sea. Because of its different shape and the difference in oceanographic conditions, the sediments of San Cristobal Bay contrast with those of the other two bays.

As long ago as 1916 McEwen pointed out the common occurrence of cold water just south of prominent points of the California and Baja California coasts. He attributed these patches to upwelling induced by sweeping away of surface water from the leeward side of the points by the prevailing northwesterly winds. Similar low temperatures were found during brief surveys of the water in San Cristobal Bay (fig. 11) even though the point at the northern end of the bay is not very prominent. Studies by Dawson (1951) have shown that such areas of upwelling are inhabited by colder water species of algae than occur in adjacent waters. The same relationship was also found for fishes by Hubbs (1948) and has been suggested for mollusks and other organisms by Valentine (1955) and Emerson (1956). Sverdrup and Allen (1939) and Sargent and Walker (1948) have shown that high concentrations of plant nutrients in the large area of upwelling south of Point Conception have produced the greatest populations of diatoms in southern California. A similar though smaller concentration of phytoplankton probably also occurs in the areas of upwelling off Baja California.

Though not proved, it is suggested that possible high concentrations of phytoplankton in the area of upwelling in the northern half of San Cristobal Bay leads to to a large food supply for mollusks and other benthonic animals—thus resulting in the observed high percentage of shells in sediments of the northern half of the bay. Because the shell fragments are coarser than the detrital grains with which they are mixed, the total sediment is coarser in the northern half of the bay than in the southern half, where no upwelling occurs. Added support is given to this hypothesis by a similar coarsening of sediments in areas just south of the several small points north of San Cristobal Bay.

TODOS SANTOS BAY

Todos Santos Bay (U. S. Hydrographic Office chart 1046) has some of the topographic characteristics of both Sebastian Viscaino and San Cristobal Bays and still it differs from each. Like Sebastian Viscaino Bay it is protected by islands near the shelf break and by a peninsula (fig. 12). The quiet water forms an excellent harbor for Ensenada, one of the principal cities of Baja California. The shelf, like that of San Cristobal Bay, possesses many minor rocky shelf knolls. In addition, the Bay contains a large deep amphitheater-like trough extending from the shelf break at about 90 m to a bottom depth of about 400 m.

At the broad head of the bay are several large intermittent streams, chief of which is San Carlos River, which gives this bay more runoff than is received by the other two bays.

Texture

The texture of the sediments was determined in the same manner as for sediments of the other two bays, with 97 samples screened and pipetted and 449 samples estimated by coding. In addition, median diameters of 70 samples analyzed by Walton (1955) in his study of foraminifers in the bay are included on figure 13.

The coarsest sediment (2 to 8 mm) occurs on the ridge between the islands and the mainland to the north (fig. 4B). Coarse sediment also exists along the shore of Punta Banda peninsula. Throughout the main protected area of the bay the grain size presents a gradual decrease from the beach (0.16 mm) to the shelf edge (0.04 mm). Slightly finer sediment (0.03 mm) covers the floor of the trough east of the islands.

Much of the sandy bottom is rippled, as shown by bottom photographs published by Shepard and Emery (1946, figure 20), which also reveal the restriction of sand to relatively flat areas and rock to shelf knolls.

Calcium Carbonate

Calcium carbonate was determined as acid-soluble fraction of 72 samples. These

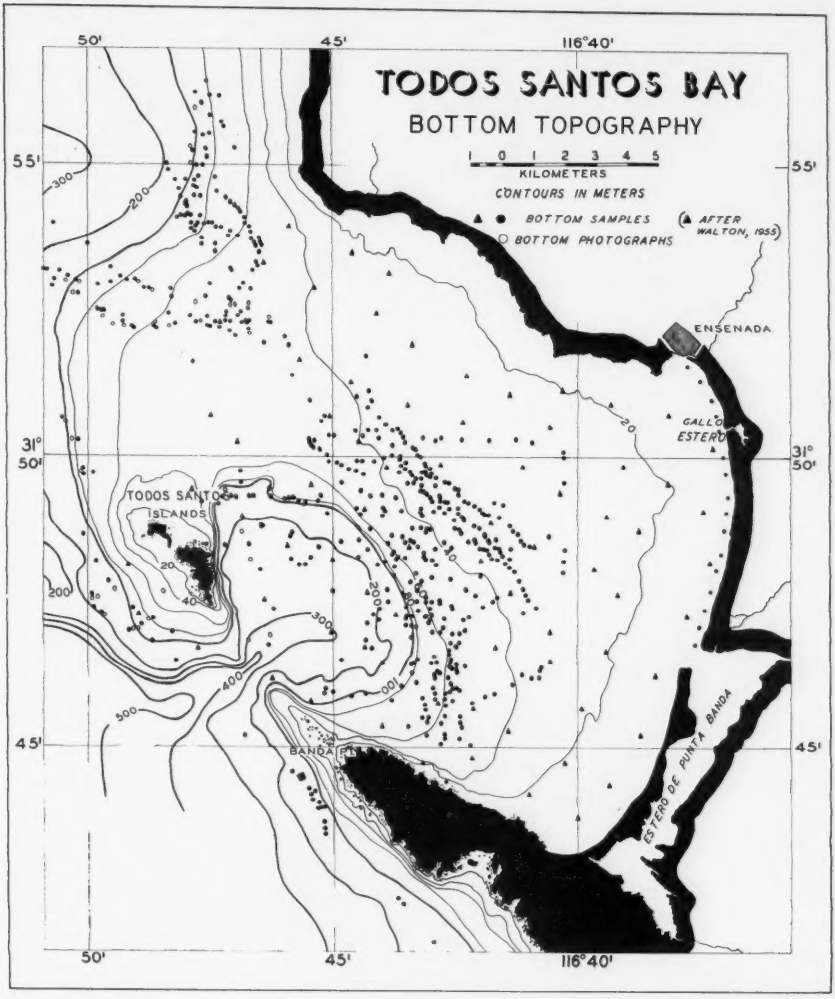

FIG. 12.—Contour map of Todos Santos Bay with contours in meters. Dots show positions of our bottom samples; triangles represent Walton's (1955) samples; circles show positions of bottom photographs.

analyses, together with results of visual examination of the samples, show that the sea floor of Todos Santos Bay can be divided into two areas that are different with respect to calcium carbonate. The larger of these areas is the gently sloping bay floor from the beach to the trough, in which calcium carbonate is mostly in the form of foraminiferal tests. Sands of beaches and of the adjoining sandy bay floor contain about 8 percent of

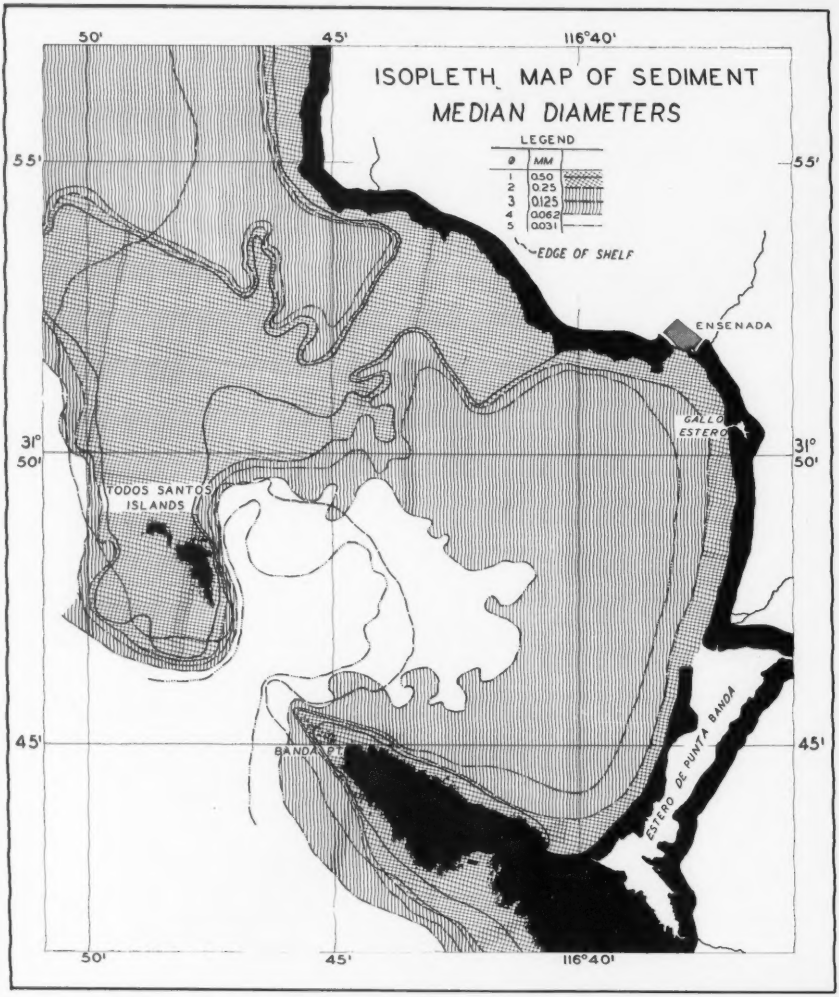

FIG. 13.—Distribution of median diameters of sediments in Todos Santos Bay based on 616 samples.

calcium carbonate (fig. 14), but with the seaward decrease in grain size the content of calcium carbonate increases to values of nearly 20 percent on the floor of the trough. This is evidently in response to a slower rate of deposition for finer than for coarser detrital sediment, which leads to differences in degree of dilution of calcium carbonate.

The second area of calcium carbonate is the ridge north of the islands and the shallow sea floor bordering the rocky parts of the mainland shore. Here the rate of deposition of detrital sediments is low, owing both to bypassing and to small supply. As a result, the sediments are coarse grained and consist chiefly of broken shells of pelecypods

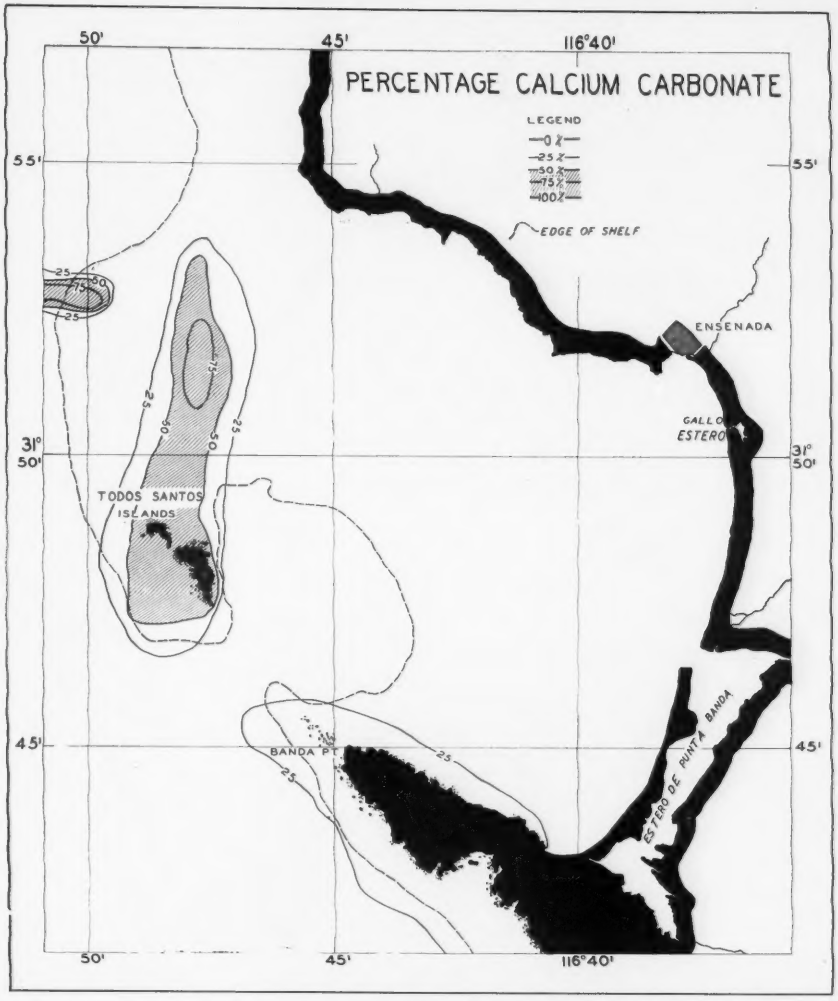

FIG. 14.—Distribution of percentage calcium carbonate in sediments of Todos Santos Bay based on acid-soluble fractions of 72 samples.

that locally comprise more than 75 percent of the whole sediment samples.

Organic Matter

The content of organic matter was computed from measurements of organic carbon, as at San Cristobal Bay. The results (fig. 15) show that organic matter comprises less than 0.85 percent by dry weight in the sediments of the ridge and most of the bay floor. Sediments of finer grain size on the outer half of the shelf and on the sides of the trough have more organic matter. The floor of the trough is covered with fine sediments

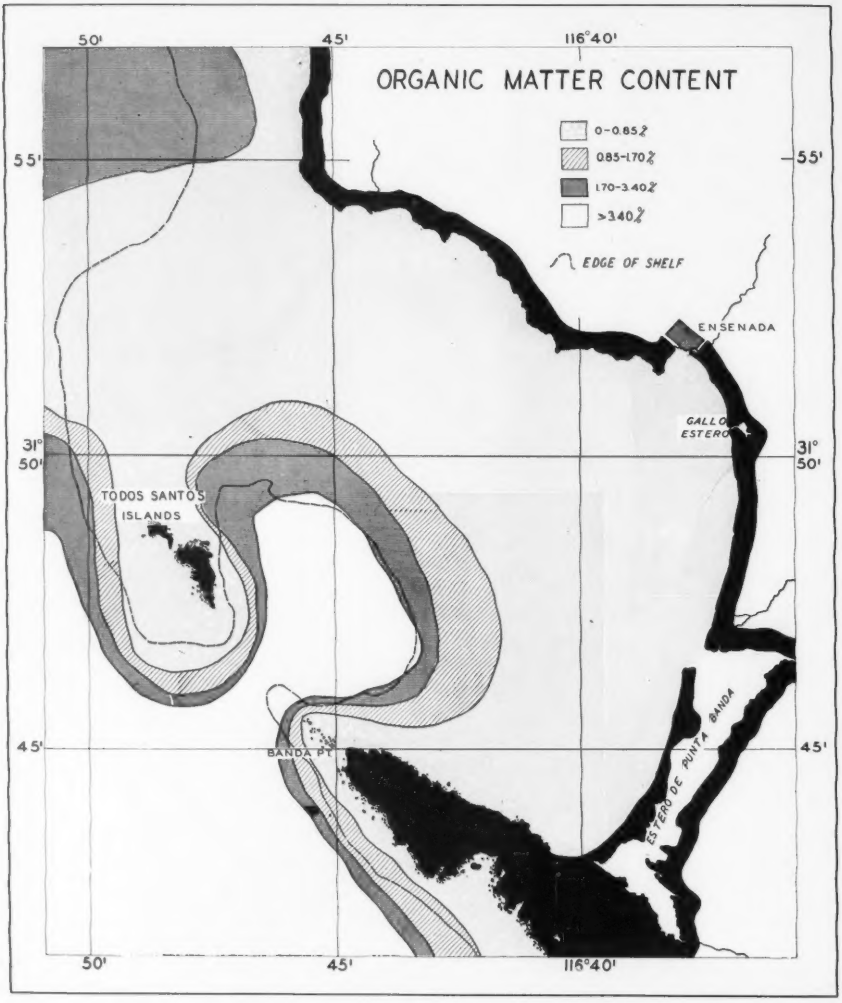

FIG. 15.—Distribution of percentage total organic matter in sediments of Todos Santos Bay, based on measurements of organic carbon in 32 samples.

having as much as 7.5 percent of organic matter.

Other Characteristics

In the area of shelly sand on the ridge north of the islands a few samples contain the authigenic mineral glauconite. Associated detrital or residual grains were found to be weathered, but less so than at San Cristobal Bay. Coprolites like those of San Cristobal Bay occur in the muddy sediment of the deep trough.

Detrital grains present in the sediments of the broad flat area of the bay consist of clean

quartz, feldspar, hornblende, and minor quantities of biotite and the other heavy minerals found at the other two bays. Heavy minerals comprise about 5 percent of the total sediment in a broad band at the edge of the shelf near the trough. Fine sediment in the trough and coarse sediment of the ridge and beach areas contain smaller percentages of heavy minerals.

Relationship to Exposure and Depth

Tidal currents and upwelling play only minor roles in the distribution of sediments at Todos Santos Bay, in contrast to their importance at the other two bays. Instead, wave action and streams appear to control the nature and distribution of sediments. In the exposed areas, such as the rocky coasts to the north and south of the bay and around the islands, erosion of the bottom by waves prevents the accumulation of fine sediments, so that only coarse detrital or relict sands and gravels and coarse shell debris can remain. Less agitation of the water at depth on the ridge permits the accumulation of greater thicknesses of shelly sediment than along the shallow rocky shores.

The small size of waves within the bay allows the deposition of sediments contributed by streams. Wave action, however, is sufficient to winnow the finest sediments out of the shallow areas, leaving well-sorted beach sands bordered by bands of progressively finer sediments at greater depth and distance from shore. It is reasonable to expect that these finer sediments are deposited less rapidly than are the coarser ones so that both calcium carbonate and organic matter are less diluted and thus comprise a higher percentage in the finer than in the coarser sediments.

CONCLUSIONS

Three Mexican bays, Sebastian Viscaino, San Cristobal, and Todos Santos, adjoin the same ocean, lie in the same climatic zone, and are bordered by similar source rocks. Nevertheless, the sediments of these bays are strikingly different, indicating the great importance of details of topography in controlling the kinds and distribution of sediments. Data are sufficiently abundant and precise to permit an evaluation of the chief factors that influence the sediments. It appears probable that the nature of sediments in these bays and on other parts of the continental shelf depends ultimately on two major factors: supply and demand. Supply is the tendency to deposit sediment; and, demand, the tendency to erode it. Detrital sediments appear to be supplied to the sea chiefly by streams, with only minor amounts contributed by wave erosion of sea cliffs, by wind, and by other agents. Demand is a function of the rate at which sediments are distributed outward from shore to their final resting places and, thus, demand is related to transporting capacity. The chief agents of of transportation on the shelf are intense local water movements, such as wave and swell with their associated nearshore currents, and tidal currents. General oceanic currents appear to play only a minor role.

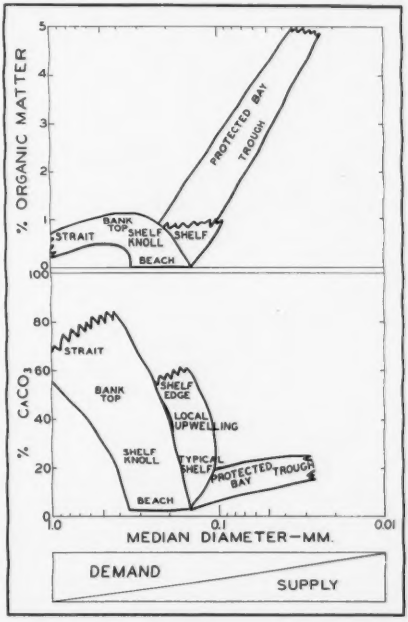

FIG. 16.—Diagram showing generalized relationship of contents of calcium carbonate and organic matter to median diameter of sediments belonging to various facies of the continental shelf. Data from the three Mexican bays are supported by studies of the shelf in southern California.

Where the rate of supply is large compared to demand, the sea bottom becomes covered with modern detrital sediments such as sand adjoining beaches, and mud in the protected areas leeward of Cedros Island in Sebastian Viscaino Bay and in the main flat floor of Todos Santos Bay. Where the rate of supply is small compared to demand, bare rock may be exposed, as in the strait south of Cedros Island and atop shelf knolls in both San Cristobal and Todos Santos Bays, and on bank tops (Ranger Bank) or ridges such as at Todos Santos Bay. Patchily covering or bordering the bare rock are sediments that commonly contain much-weathered residual sands. Because detrital sediments are deposited only slowly or not at all in these areas, material precipitated or organically extracted from sea water may dominate. Chief of these materials is coarse shell sand, but coarse authigenic minerals such as phosphorite, glauconite, and pyrite may locally be common. In other areas sediments may be relict, or inherited from a former time of lower sea level.

Evidence denoting the relative rates of supply and demand often can be read from the sediment itself. In the study of the Mexican bays the three most obvious kinds of information are median diameter, content of calcium carbonate, and content of organic matter. Values of these parameters for the Mexican bays are similar to averages compiled by Emery (1954) from many environments of southern California.

A diagrammatic presentation of the data from this study is given by figure 16, as plots of median diameter against contents of calcium carbonate and organic matter. Median diameter is a reasonably good indicator of relative current velocity except where supply very greatly exceeds demand (not true in any of the Mexican bays). In areas that have a more intense demand relative to supply than do beaches, the sediments are coarser and they contain more calcareous shell material, which itself increases the median diameter of total sediment. The coarseness of this material permits only a low content of organic matter. In order of decrease of rate of supply relative to demand are: beaches, shelf knolls, bank tops, and straits, all of which are represented among the three bays.

A different situation exists where demand has been reduced below supply in areas of deep water or protection by islands, represented at Todos Santos and Sebastian Viscaino Bays, respectively. Some of the finer sediment that by-passes the beaches is deposited in such areas, but deposition is so slow that foraminiferal tests are only slightly diluted by detrital grains, causing the content of calcium carbonate to rise to moderate values (fig. 16). Fine grain size is accompanied, as usual, by very high contents of organic matter.

Areas of simple continental shelves, uncomplicated by topographic and shoreline irregularities should and apparently do have sediments intermediate between those of the two extremes already discussed (fig. 16). Highest contents of calcium carbonate exist in shelf reas of upwelling or at the outer edge of the shelf where the supply-demand ratio approximates that of bank tops.

It is perhaps uncertain whether continental shelf deposits have been preserved in the geological record, but if so, such data as that of figure 16 may aid in their recognition and delineation. Certainly this kind of information would be extremely useful in locating ancient shorelines, for example. Probably a similar analysis of facies in broad shelf areas would be helpful in study of sediments of ancient epicontinental seas.

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FIGS. 1–12, JUNE, 1957

DIFFERENTIATION OF MARINE AND SUB-AERIAL SEDIMENTARY ENVIRONMENTS BY VOLUME PERCENTAGE OF HEAVY MINERALS, MUSTANG ISLAND, TEXAS

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ABSTRACT

The marine and sub-aerial sedimentary environments across Mustang Island, Texas, can be differentiated by the volume percentage of heavy minerals in the sediments. The barrier island sediments average .45% heavy minerals and the gulf sediments average .04% heavy minerals. The berm, averaging .34% heavy minerals, is the transition zone between the environments. Analyses of the amount of heavy minerals may be valuable in characterizing the environment of deposition of ancient sediments.

INTRODUCTION

As part of a detailed study of the beach and laterally adjacent environments on Mustang Island (fig. 1) a series of heavy-mineral analyses were made. Although no differentiation of environments could be made mineralogically, it was noticed that the amount of heavy minerals in a given volume of sediment fell within one of two rather rigid classes. A further check of volume percent of heavy minerals defined these two classes (fig. 2). It was found that the sub-aerial sediments of the barrier contained from .36% to .60% heavy minerals and the gulf and bay sediments contained from .02% to .12% heavy minerals. The berm (fig. 3) is the transition zone between the two classes and contains from .16% to .64% heavy minerals. If marine and adjacent sub-aerial environments are found to be differentiated by volume percentage of heavy mineral in other coastal areas, this method, in conjunction with the methods described by Shepard and Moore (1955) for the adjoining Rockport area, may be used to characterize the environment of deposition of ancient sediments.

DESCRIPTION OF AREA

Mustang Island (fig. 4) is one of the series of barrier islands lying along the Gulf coast of Texas. It separates Corpus Christi Bay from the Gulf of Mexico and is 18 miles long and 1½ to 5 miles wide. Corpus Christi Pass which separates Padre and Mustang Islands on the south is closed but Aransas Pass to the north between Mustang and St. Joseph Islands is jettied and regularly dredged.

The climate is semi-arid with average annual rainfall of 28 inches (Corpus Christi, 66 year average) but in the last 2 years the rainfall has averaged only 19 inches. The excess of evaporation over precipitation has averaged 21 inches.

A section across Mustang island (fig. 3) shows the continental shelf rising evenly and gently to about −25 feet at the toe of the shoreface. From −25 feet to +3 feet the shoreface and beach rise evenly, but more steeply, to the berm face. Bars (fig. 5), five under normal wind and tide conditions, are built from 1 to 2 feet high and 20 to 50 feet wide on the shoreface from the beach to about −11 feet. The berm face (fig. 6) rises from the top of the beach face about ½ to 1 foot to the berm crest (fig. 7), from which the berm flat (elevation 3 to 5 feet) extends inland to the dunes. In blowout and washover areas the berm flat may extend inland through the dunes to and about the level of the barrier flat. Transient dunes (fig. 8) from 1 to 12 inches high are found on the berm flat. Three foredune chains (fig. 9) parallel the beach. The first ridge of dunes rises about 3 feet above the berm flat and is sparsely vegetated. In some areas the ridge has grown back onto the face of the second ridge dunes and in other areas it has been obliterated by the sea. The second ridge of dunes extends the length of the island and rises to an elevation of 10 to 20 feet. It is well stabilized by vegetation. A third ridge

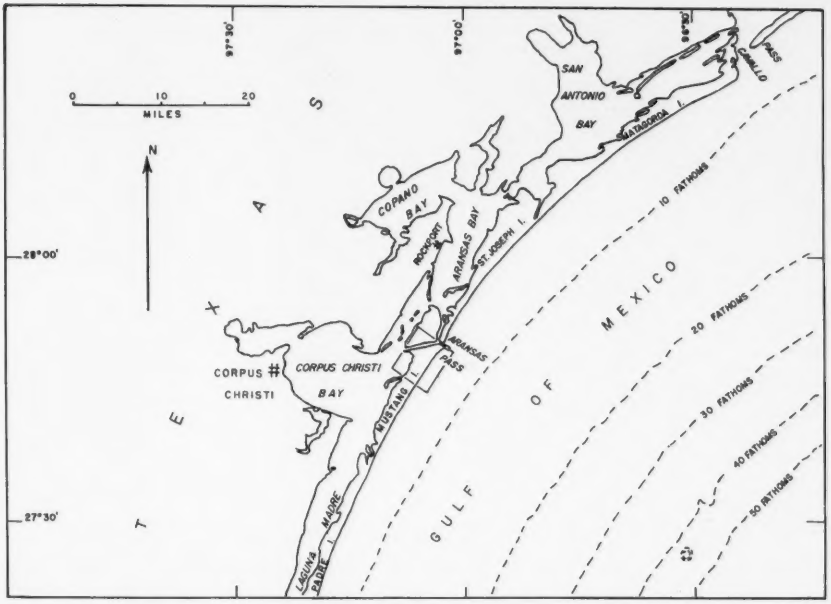


FIG. 1.—Area location map.

of large, heavily vegetated dunes rises to elevations of 25 to 45 feet. The stabilized foredune ridges tend to be higher and more regular toward the north end of the island. The barrier flat extends bayward from the back of the large dunes at an elevation 5 to 2 feet. Stringers of dunes and small individual dunes (fig. 10) are found on the barrier flat and can usually be associated with old blowout areas. Large areas of the bay side of the island are tidal flats which are periodically flooded by bay waters.

Several blowouts (fig. 11) occur through the dune ridges. They are formed when vegetation on the dunes dies, usually because of drought, and the wind moves the unstabilized sand inland. Live migrating dunes (fig. 12), up to 10 feet high, string out across the barrier flat. Sand is provided from the foredune ridges and from the berm. The

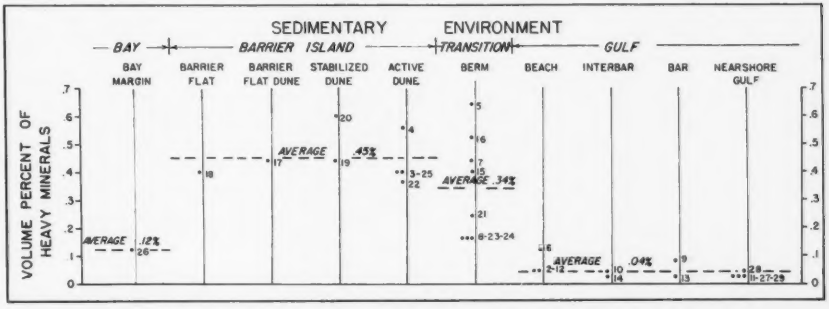


FIG. 2.—Volume percentage of heavy minerals in sediments of various environments.

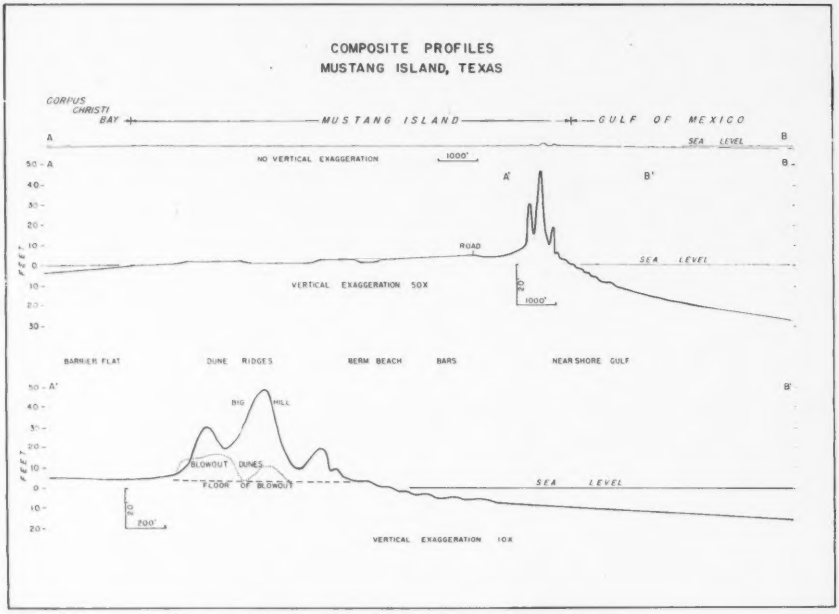


FIG. 3.—Composite profiles across Mustang Island.

floor of a blowout appears to be controlled by the water table, the wind removing all dry sand to within an inch or two of the water table surface. This surface extends inland from the berm flat at approximately the berm level and is conveniently referred to as the berm extension. If the water table rises, the floor of the blowout builds up by accretion of dry sand blowing onto the damp surface.

Washovers are low areas through the dune ridge and across the barrier flat through which sea water flows to the bays during storm tides. These areas are generally lower than blowout areas and connect with extensive tidal flats on the bay side of the island. The berm is the high point on their profile and acts as a dam across the mouth of the washover for normal tide conditions. The new (October 1955) highway the length of the island acts as a dam (+5 feet) which has to date prevented washover into the bay. Washovers may be associated with blowouts and it is sometimes difficult to establish the precedence of one to the other.

Sediments in the area are fine and very fine sands with minor amounts of coarse shell and silt. Clays are found seaward at approximately −25 feet and inland on the tidal flats and in the bay.

METHODS OF STUDY

Field.—Sample collections were made in three areas on the north half of Mustang Island (table 1). All samples, except numbers 2 and 18, are surface samples. Gulf and bay samples were taken from a boat with a 1-pint, positive-action, snapper dredge which samples approximately the top 2 inches of the sediment. Bar and interbar samples were taken by swimming from the beach. Sample number 1 was taken from a black band of heavy mineral concentration, at the base of a large blowout dune after a heavy rain and represents the top 1 mm of sediment.

The three areas sampled have for convenience been named "Big Hill," "Blowout," and "Road Blowout" (fig. 4). Big Hill is the highest point on Mustang Island and

TABLE 1.—*Locality description; Localities are plotted on map, figure 4*

Sample Number	Area	Description
1	Blowout	Base of large live dunes, 150 yards inland from fence line
2	Blowout	Beach face, 50 yards seaward from fence and 5 inches below surface in reducing environment
3	Blowout	Live dune top, 150 yards inland from fence line
4	Road Blowout	Live dune top, at fence line along east side of road
5	Blowout	Berm, 10 feet seaward from fence
6	Blowout	Beach face, 50 yards seaward from fence
7	Big Hill	Low dune on back of berm
8	Big Hill	Berm front
9	Big Hill	Face of fourth bar in 4 feet of water
10	Big Hill	Interbar between third and fourth bars in 4 feet of water
11	Big Hill	Gulf bottom seaward of last bar in 12 feet of water
12	Big Hill	Beach face
13	Big Hill	Bar top, third bar in 2½ feet of water
14	Big Hill	Interbar between first and second bars in 1 foot of water
15	Big Hill	Berm front, wind eroded
16	Big Hill	Berm flat, thin wind rippled sand
17	Blowout	Stabilized dune on barrier flat 50 feet inside fence on west side of road
18	Blowout	Barrier flat sand, 2 inches below surface (below grass roots) 75 feet inside fence on west side of road
19	Big Hill	Stabilized dune 100 feet inland from berm flat
20	Big Hill	Stabilized dune 400 feet inland from berm flat
21	Big Hill	Small live dune at back of berm flat
22	Road Blowout	Live dune inside fence on west side of road
23	Blowout	Small live dune on berm extension 60 yards inland from fence
24	Blowout	Small live dune on berm extension 25 yards inland from fence
25	Blowout	Lee face of large live dune 150 yards inland from fence
26	Big Hill	Corpus Christi Bay, 200 yards into bay in 3 feet of water
27	Big Hill	Gulf bottom in 14 feet of water
28	Big Hill	Gulf bottom in 20 feet of water
29	Big Hill	Gulf bottom in 25 feet of water

lies in the third range of foredunes from the beach 4¼ miles south of the Aransas Pass south jetty. A profile across the island at approximately right angles to the beach trend was established through Big Hill. This area was chosen because of the nearby access road and because it is far enough south to minimize any effect of the jetties.

Blowout is a small area of live migrating dunes, 1 mile south of Big Hill, which extends about 250 yards from the beach, through the dune ridge, to the barrier flat.

Road Blowout is an area of live migrating dunes, 2½ miles south of Big Hill, which extends from the beach about a half mile across the barrier flat to the Port Aransas-Corpus Christi highway.

Laboratory.—All samples were washed three times with fresh water and dried. The washings of sample number 29, a sample with clay-size sediments, were settled and the clay measured in a sediment (sewage) cone. For size analyses, 100 ml portions of 7 samples were mechanically shaken for 15 minutes through a series of sieves, 40, 60, 80, 100, 120, 150, 200, and pan, N.B.S. mesh. The amount of sample on each sieve was measured to the nearest 1 ml, i.e., to the nearest 1% by volume.

For heavy mineral analyses, 25 ml portions of each sample were added to 25 ml of Bromoform, specific gravity 2.89, in 100 ml pear-shaped centrifuge tubes. The tubes were tapped, shaken, and stirred periodically for at least 5 hours or until no further sedimentation was observed. The amount of heavy minerals was read directly from the graduated tube.

The centrifuge tubes are an inverted cone with a small cylinder extending down from the apex of the cone. The cylinder is graduated into twentieths of a milliliter and the distance between graduations is 2 mm. The graduate can be easily read to ⅕ of a division and tenths of a division can be estimated. In terms of the total sample, the

TABLE 2.—*Heavy mineral analyses*

Sample Number	Description	Volume % Heavy Minerals
1	Base of live dune at HM concentration	17.00
2	Beach face, 5″ below surface	.16
3	Live dune top	.40
4	Live dune top	.56
5	Berm	.64
6	Beach face	.12
7	Berm	.44
8	Berm	.16
9	Bar	.08
10	Interbar	.04
11	Gulf	.02
12	Beach face	.04
13	Bar	.08
14	Interbar	.08
15	Berm	.40
16	Berm	.52
17	Stabilized dune	.44
18	Barrier flat	.40
19	Stabilized dune	.44
20	Stabilized dune	.60
21	Berm	.24
22	Live dune	.36
23	Berm extension	.16
24	Berm extension	.16
25	Live dune	.40
26	Bay	.12
27	Gulf	.02
28	Gulf	.04
29	Gulf	.02

divisions give a .2% direct reading, a .04% accurate interpolation, and a .02% estimate. As the bottom of the cylinder is hemispherical, readings less than about .06% are estimates.

RESULTS

Analyses of 29 sediment samples taken across Mustang Island show that marine and sub-aerial sedimentary environments may be differentiated by the volume percentage of heavy minerals in the sediments (table 2 and fig. 2). The sub-aerial sediments contained from .36% to .60% heavy minerals with an average of .45%. The marine sediments contained from .02% to .12% heavy minerals with an average of .04%. Sediments from the berm, which comes under influence of both wind and water, varied from .16% to .64% heavy minerals with an average of .34%. The one bay sample contained .12% heavy minerals.

No detailed mineralogic study of the heavy-mineral fraction was made because a check of the samples showed no significant or systematic variation from the results of the investigations of Bullard (1942), Goldstein (1942), Lohse (1952), and Shepard and Moore (1955). The sedimentary en-

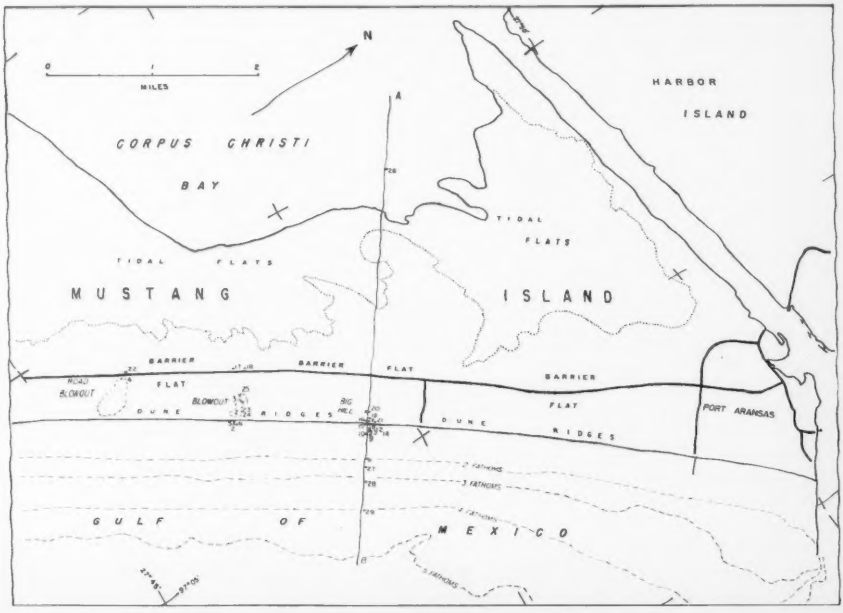
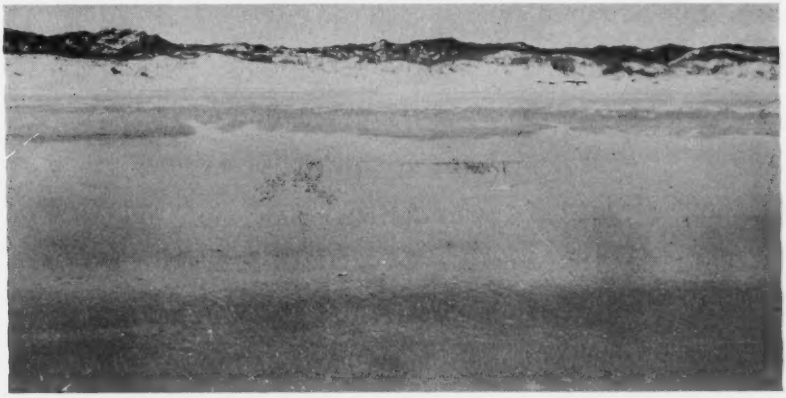


FIG. 4.—North half of Mustang Island.

FIG. 5.—Bar cut by rain wash at extreme low tide. Second bar in foreground, rippled interbar area, first bar in middleground (eroded), beach face, berm flat in background. Note the berm extension through the dune ridges in this washover-blowout area.



F.G. 6.—Wind blown sand (light) filling the berm face and rain-cut channels in the berm. Beach face in foreground, berm flat in middleground, dune ridges in background.

FIG. 7.—Runoff from heavy rains cutting the berm. The cut is a maximum of 22 inches deep.

TABLE 3.—*Size analyses*

Sample Number	Description	Volume %			
		Fine Sand	Very Fine Sand	Silt	Clay
5	Berm	61	39	—	—
14	Interbar	60	40	—	—
19	Stabilized dune (front)	61	39	—	—
20	Stabilized dune (rear)	73	25	1	—
25	Live dune	72	28	—	—
27	Gulf, 12′ water	4	92	3	—
29	Gulf, 25′ water	8	77	11	4

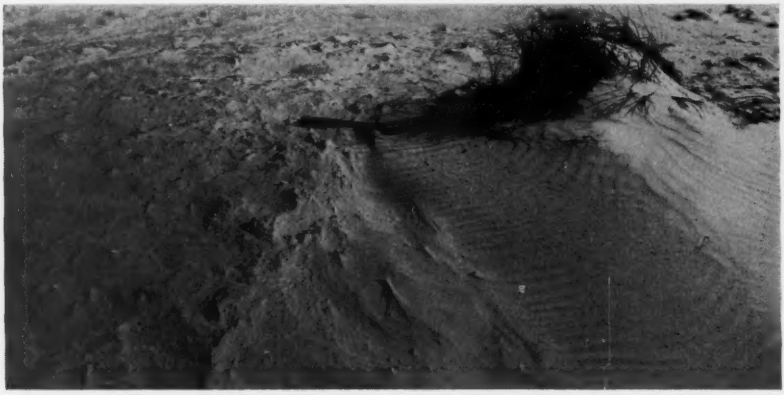


FIG. 8.—Wind scour and fill on the berm flat at Big Hill. A storm later removed the small vegetated dune.

FIG. 9.—Dune ridges near Big Hill. First dune ridge above beach at right, second dune ridge down the middle and in foreground, third dune ridge inside fence at left.

FIG. 10.—Barrier flat and barrier flat dunes (vegetated). Tidal flats and Corpus Christi Bay in background.

vironments could not be differentiated mineralogically.

The results of size analyses of 7 samples (table 3) from various localities agree with the results of Shepard and Moore (1955) from the adjoining Rockport area. Beach and dune sands are from 60% to 75% fine sand and 25% to 40% very fine sand (Wentworth grades). Near shore gulf sands are from 75% to 95% very fine sand. Clay first appears in samples from 25 feet of water.

DISCUSSION

The process by which the volume percentage of heavy minerals is increased in sub-aerial environments is evidently related to the work of the wind. During the winter, north winds blow a great deal of sand south across the island and onto the berm and beach, however, as is obvious from the alignment of the blowouts, net movement of sand is to the northwest by southeast winds. The source of the heavy minerals, and the dune sands, is the sea. The enrichment process may be related to the selectivity of the heavy minerals by wind blowing across the beach or to selectivity of light minerals by wind blowing across the dunes. The heavy minerals, especially the opaques, tend to be more rounded than the light mineral grains. Shepard and Moore (1955) note that the dune sands are distinctly more rounded than sands from other environments and they attribute this enrichment of more rounded sediments to selective transportation from the beaches rather than to lag concentration. If the heavy mineral concentration were a lag deposit, sediments farther inland might be expected to have smaller percentages of heavy minerals. There does not appear to be a diminishment of heavy minerals across the island and thus it is concluded that selective transportation by wind from the beach is the mechanism for heavy mineral concentration.

This selective transportation may be due to the greater roundness of the heavy minerals or may be related to competence of wind with respect to a certain volume-weight ratio. Most of the heavy minerals are smaller than the accompanying light minerals, i.e., the heavy minerals are separated on the 200 mesh sieve (very fine sand) and in the pan (silt). Their specific gravity ranges from 3 to 5. It may be that the wind has higher competence with respect to the heavy minerals as it has been noted in dune areas that the dark (heavy) minerals may be slightly concentrated on the lee face and in the valleys of small wind ripples. If the heavy minerals were a lag concentrate, the concentration should appear on the windward face of the ripples.

The frequency of blowouts with sand banners migrating across the barrier island varies with the climate. Galveston Island, Matagorda Peninsula, and Matagorda Island show more blowouts toward the

FIG. 11.—Blowout area as seen from the berm. Live dunes are crossing the third dune ridge (background).

south as the climate changes from moist-subhumid to semi-arid. St. Joseph Island, immediately north of Mustang Island, is a stabilized dune area with few blowouts and has the southernmost occurrence of "beach ridges." Mustang Island has no beach ridges but is primarily a stabilized dune area with occasional blowout areas. Large blowout areas cover southern Padre Island with migrating dunes. Although the wind velocity and duration are roughly comparable along the Texas coast (Bretschneider and Thompson, 1955) the work of the wind varies with the amount of moisture which, in turn, controls the vegetation stabilizing the sand. Several cycles of comparative aridity are indicated by old, now vegetated, blowout areas on the barrier flat of Mustang Island. Price and Gunter (1942) note that the long range climatic trend is toward aridity. Padre Island was green until shortly after 1870 when it became greatly denuded. The record rains of 1941 and 1942 restored some green cover on the north half of Padre Island and on Mustang Island. The ensuing drought has started new series of blowouts.

After a heavy rain late in 1955, the road blowout area underwent several changes. The dunes had become water logged and as they slowly dried the wind rounded and

FIG. 12.—Road Blowout area looking south along highway. Dune ridge at left, barrier flat in foreground. The blowout extends about 100 yards across the road (right).

subdued them. Within a few weeks many plants had sprouted in the bare dune area and were effectively stabilizing the sand. As the water table subsided and as there was no more rain, the vegetation died and the sand is again blowing and building large angular dunes. The balance between blowing sand and stabilized conditions on Mustang Island is very delicate. A slight increase in precipitation would cause a bloom of vegetation and blowing sands would be essentially restricted to beach and berm areas.

It is not known how much work of the wind is required to give the higher concentration of heavy minerals which allows the differentiation of sub-aerial and marine environments. This method for characterizing sedimentary environments may or may not work on Galveston Island which is essentially a series of beach ridges. After investigation of the beach ridges on St. Joseph Island, Shepard and Moore (1955) state that from roundness studies the sands of the ridges are of dune type as much as 7 feet below the surface. It may be that the beach ridges are a series of higher than normal, and hence preserved, berms. The heavy-mineral concentration of berm samples, particularly those which were obviously worked by the wind, indicate that relatively little exposure to wind is required for concentration and it seems probable that this method of delineating environments will work in beach ridge areas as well as in dune areas.

The berm is built up from sand carried by the surf during infrequent periods of high water. Occasionally, a secondary berm will be formed lower on the beach during extended periods of low water with high surf. Most of the time the berm is cut and filled by the wind and may become indistinct. The berm receives sand thrown up by the sea during high water, and blown from the beach at normal and low water stages with the prevailing southeast wind, and from the dunes with the north winter winds. The dual origin of the sands is reflected in the concentration of heavy minerals (fig. 2).

Bullard (1942) noted lamination of dark and light sands on the beach. Price (personal communication) saw bands of dark sediments up to 2 inches thick in the beach and berm on southernmost Padre Island. No lamination or segregation of dark minerals was found on the beach or berm during this study of Mustang Island.

CONCLUSIONS

Sub-aerial and marine sedimentary environments may be differentiated by the volume percent of heavy minerals in the sediments on Mustang Island. The marine samples average .04% heavy minerals, the barrier island samples .45% heavy minerals, and the berm (transition) .34% heavy minerals. No differentiation of environments could be made mineralogically.

Selective transportation by wind from the beach appears to be the mechanism for heavy mineral concentration. Selection may be related to greater roundness of the heavy minerals and to competence of wind with respect to the volume-weight ratio.

The volume percentage of heavy minerals may characterize the environment of deposition of ancient sediments.

ACKNOWLEDGMENT

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FIG. 1, JUNE, 1957

A BAHAMIAN FAECAL-PELLET SEDIMENT

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ABSTRACT

The sediment in the extreme northern portion of the lagoon of the island of Bimini, B.W.I., consists principally of elongate tapered pellets. These distinctive pellets were identified as excrement from *Batillaria minima*, a marine gastropod abundant in the area of pellet accumulation. Since this gastropod is ecologically restricted, the occurrence of such pellets *in situ* in the fossil record would be of paleoecological significance.

INTRODUCTION

In the course of an investigation of the general ecology and sedimentation of the Bimini, British West Indies region[1] under the direction of Norman D. Newell, the authors discovered an area in the northern extremity of the Bimini lagoon in which at least 90% of the sediment is composed of a single type of faecal pellet (fig. 1). The marine gastropod, *Batillaria minima* (Gmelin), occurs abundantly in the same area. When isolated in a glass bottle, individuals of this species excreted pellets identical to those observed in the sediment; thus there is no doubt that *Batillaria minima* is the organism responsible for the pellets here described.

So far as the authors know, this type of pellet has not been previously described in Bahamian literature.

DESCRIPTION OF PELLETS

The light brown to gray colored pellets of *Batillaria minima* are emitted in the form of a tapering rod which is circular in cross section, rounded on each end, and is without surface sculpturing. The average length of these rods is 0.90 mm; the average maximum diameter is 0.16 mm. These pellets are extremely fragile when first excreted.

When a pellet is placed in cold 5% hydrochloric acid, a brisk effervescence occurs. Completion of this reaction leaves a minutely pitted mass of organic mucus identical in general shape and size to the former intact pellet. Evidently, the pellets are composed of silt-sized calcareous particles embedded in organic mucus. Microscopic examination of a smear of this mucus (1800×) reveals the presence of numerous small algal bodies.

Faecal pellets of *Batillaria minima* were compared with those of many of the marine organisms living in the Bimini area and with the photographs of faecal pellets published by Illing (1954, plates 1.1, 3.1, and 3.2) and found to be distinguishable.

PRESERVATION

While it is true that these pellets will disintegrate at a pin prick when first excreted, there are several reasons why such fragility does not result in the destruction of the pellets, as evidenced by their abundance. First, the current velocity of the northern extremity of the Bimini lagoon is quite small (we have recorded a current velocity of only .01 meter/sec. for an ebbing tide in the area), and therefore any pellet destruction caused by current action would presumably be negligible. Secondly, the area is emergent during low spring tides, and laboratory observations indicate that desiccation results in the permanent hardening of the pellets. A probable third factor in the preservation of the pellets is the scarcity of organisms whose movements might result in the destruction of the pellets. A fourth possible factor is the bacteriological precipitation of aragonite within the pellet (Illing, 1954).

Additional evidence concerning the durability of the pellets was obtained from a 22 cm sediment core taken immediately south of the area previously described. Examination of the bottom of this core revealed the presence of hardened faecal pellets of

[1] Our base of operations at Bimini was the Lerner Marine Laboratory of the American Museum of Natural History.

FIG. 1.—Photomicrograph of faecal pellet sediment from the northern extremity of the Bimini lagoon. ×13. Insert of *Batillaria minima* (Gmelin). ×2.

Batillaria minima, thus demonstrating that these pellets are capable of preservation.

OCCURRENCE

Bequaert (1942, p. 9) gives the geographic range of *Batillaria minima* as: Bermuda; Florida; the West Indies; the Caribbean shores of Central and South America, as far east as Bardados; and the Gulf of Mexico, as far north as Vera Cruz. Examination of appropriate sediments in these areas may reveal faecal-pellet sediments comparable to those described in this paper.

Bequaert observes that *Batillaria minima* is often found in shallow, brackish water, where it lives on intertidal mud flats. Our studies in the Bimini area have shown that this gastropod is also abundant in shallow, marine waters where the salinity commonly exceeds the normal. For example, the salinity of the water in the northern extremity of the Bimini lagoon has been observed to reach at least 45°/₀₀ (Turekian, 1956).

It is interesting to note that Dall (1905, p. 44) reported collecting *Cerithium septemstriatum* (=*Batillaria minima*) from the marine limestone of the Bahamas. Thus, it seems likely that a detailed examination of Bahaman limestone will reveal the presence of the fossilized pellets of this organism.

SUMMARY AND CONCLUSIONS

1. A major portion of the sediment in the northern extremity of the Bimini lagoon consists of the faecal pellets of *Batillaria minima*.

2. These pellets are distinguished from those of other marine organisms living in the region by their characteristic shape.

3. These pellets are capable of preservation.

4. Since *Batillaria minima* is ecologically restricted, the occurrence of its distinctive pellets *in situ* in the fossil record would be of paleoecological significance.

5. It is likely that there are other areas in which the faecal pellets of *Batillaria minima* constitute a significant proportion of the sediment.

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FIGS. 1–8, JUNE, 1957

FLUME EXPERIMENTS ON THE PRODUCTION OF STRATIFICATION AND CROSS-STRATIFICATION[1]

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ABSTRACT

Experiments are being conducted in flumes designed to simulate conditions of deposition (1) through stream current action, and (2) by slumping into a standing body of water. Previous experiments, made in a wind tunnel with dry sand, formed deposits (1) by wind currents and (2) by avalanching down steep slopes. Stratification, or cross-stratification, was developed under each of the four environments of deposition. The type of deposit formed depends upon such factors as speed of current, depth of water, size of grain, degree of sorting.

Significant observations from the experiments include: (1) Foreset beds develop without bottomset beds where sorting is good and clay minerals are absent or sparse. (2) Topset beds commonly are eliminated in delta-front deposits through lowering of the water level. (3) Wind-deposited sand on the lee sides of dunes forms strata with dips that consistently are several degrees greater than those of foreset slopes in water-deposited sand of corresponding grain size and texture. (4) Channel profiles tend to be U-shaped where formed by streams flowing down the channel bottoms, semicircular where formed by currents in a standing body of water that fills the channels. (5) Cross-stratification that appears to be upside down, consisting of festoons that are convex upward, can be formed by coalescing lobes at the front of an advancing delta; strata in channel-fills, including "festoon" types, vary from those that curve in conformity with the channel to those that are nearly flat-lying as a result of differences in position of water level at or above the channel rims during deposition.

METHODS AND OBJECTIVES

Experiments now in progress have been designed to reproduce various primary sedimentary structures in the laboratory, especially common types of stratification and cross-stratification. The objective of this work is to obtain qualitative data that (1) will aid in the genetic interpretation of similar structures in ancient rocks and (2) will indicate which specific factors are responsible for each variation in a structural pattern.

This paper is a progress report on a long-range program of investigation. Work was begun by the writer in the sedimentation laboratory at the University of Arizona in 1950, where experiments were made, first with the assistance of George Williams and later of Charles Evenson, over a three-year period (McKee, 1953). Since 1953 the program of study has been continued, using more elaborate equipment in a laboratory established by the U. S. Geological Survey at Denver, Colorado. A small part of the laboratory program conducted in Denver and included in this report has been the work of Steven Oriel and the author.

[1] Publication authorized by the Director, U. S. Geological Survey.

Equipment used in experimental work has included a stream-flow tank, made entirely of metal, 15 feet long, 2½ feet wide, and 1 foot deep, and a delta tank that is similar, except that it is 2 feet deep and has a moderately steep bottom slope at the forward end of which foreset or delta-front deposits can be developed. Both are equipped with outlet valves at several heights to allow raising or lowering of water level at different rates. A third tank, 45 feet long and equipped with a baffle to generate waves, is in use but will not be reported on at this time. Experiments with dry sand also have been conducted in the delta tank.

A satisfactory method of recording structure patterns has been worked out during the experiments. Stratification planes, as they develop, are marked by sprinkling fine magnetite grains on the sediment surface. In this manner dark reference layers or bands are formed within the accumulating light-colored sands. This stratification subsequently is preserved for later observation by (1) draining off the water, (2) cutting through the deposit with a long knife to form a smooth, vertical section, (3) impregnating the freshly exposed surface with liquid rubber spread on a thin board, and finally (4) slicing the impregnated face of

sediment free from the mass and lifting it onto the board to dry.

Certain limitations are apparent in the experiments as conducted thus far, though they probably do not detract appreciably from the value of the program. One is that the small size of the tanks makes possible the study of only small-scale structures. A second is that the deposits are not subjected to compaction, and therefore various structures have slopes and dips that may not be directly comparable to those of indurated rocks. Finally, the speed and turbulence of the water cannot attain magnitudes as great as those responsible for certain types of structures developed in nature, and deposits must necessarily be largely of types resulting from slow, even flow. However, even though the models have not been scaled down mathematically, results probably are reasonably satisfactory because emphasis has been on processes rather than on structures of specific dimensions.

VARIATIONS IN DIP OF FORESET BEDS IN CROSS-STRATIFICATION

Many experiments have been made, especially by engineers, on the angle of repose of unconsolidated sediments, and an extensive literature on the subject is summarized by Van Burkalow (1945). Nevertheless, because the present studies of cross-stratification show many variations dependent on the particular sediments used, experiments were undertaken to investigate differences in the dip of foreset beds formed under both subaerial and subaqueous conditions and to determine their causes. One variable was changed at a time during these experiments, all other factors being kept constant. Variables included size of grain, roundness or angularity of grain, presence or absence of clay, convexity (in plan view) of slope on which deposited, and velocity of water.

Descriptions of individual experiments have been presented in an earlier report (McKee, 1953). Results indicate that in a standing body of water the slope representing the angle of repose for various types of sand is consistently steeper by approximately 1 to 3 degrees where (1) the sand is angular rather than rounded, (2) the grains are coarse rather than fine (fig. 1), (3) clay is absent, (4) sorting is poor, and (5) the velocity of the transporting water that introduces the sediment into the standing body is decreased 2 to 4 times. Such variations are a function of friction versus gravity. Any combination of the influencing factors will determine the angle of repose for a particular stratum of sand. Though these factors cause moderate deviation from an average slope, they do not seem to be sufficiently effective to change the normal foreset surface of subaqueous sand deposits beyond the range of about 25 to 30 degrees from the horizontal.

Under subaerial conditions, the same factors that influence the slope of water-deposited foreset beds control the angle of repose. Furthermore, changes are generally of the same order of magnitude, from 1 to 3 degrees. The presence of clay, however, may result in differences of angle of repose of a

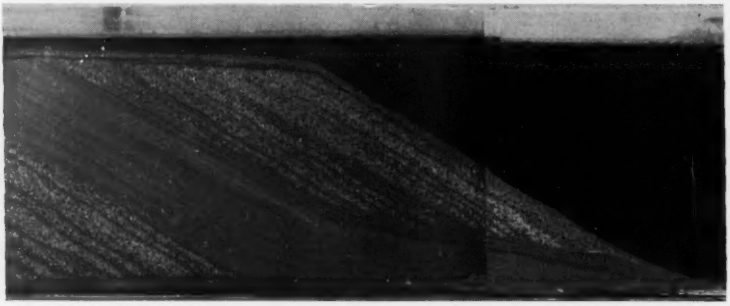

FIG. 1.—Subsets of cross-strata formed of coarse, sorted sand (left); fine sand with silt and clay (center); coarse, sorted sand (right). Shows higher angle of coarse sand and partial beveling of top surface, and formation of bottomset beds of fine sand, silt and clay. Subaqueous.

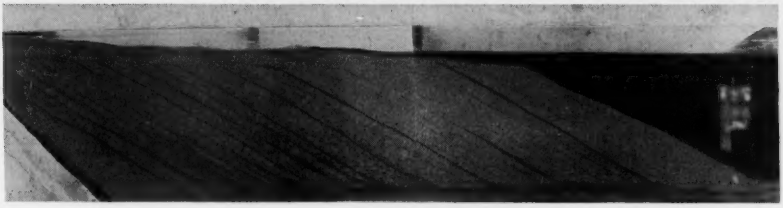

FIG. 2.—Changes in stratification due to changes in velocity. Decrease in dip of foresets and increase in amount of bottomsets (left to right) due to increased velocity.

greater order of magnitude. In dry sand the clay serves as a binder and increases the angle of repose considerably, whereas in wet sand it acts as a lubricant and lowers the angle. Significant is the fact that, for any given size and shape of grain, eolian deposits consistently attain an angle of repose 3 to 7 degrees greater than in comparable deposits formed subaqueously. Thus, wind-deposited sand strata normally attain angles of repose ranging from 30 to 35 degrees from the horizontal.

BOTTOMSET AND TOPSET BEDS

In experiments involving deposition by streams into a standing body of water, bottomset beds did not develop where sand was well sorted. In contrast, where poorly-sorted sand was used, the finer grains tended to move farther down the slope than the coarser; this resulted in a curving, rather than a flat surface, tangential with the underlying surface. When clay occurred in the sand, the downslope decrease in angle was even more pronounced, and prominent fine-grained bottomset beds formed (fig. 1). Therefore, the degree of sorting and especially the presence or absence of clay particles seem to be significant in determining whether bottomset beds are developed.

Bottomset beds were developed also as a result of changes in velocity of the depositing stream (fig. 2). During a series of stages in which speed of the water was doubled each time, sediment consisting of well-sorted, medium-grained sand showed a progressive reduction in angle of bedding planes and the original straight, even surfaces changed to irregular, curving surfaces. As water velocity increased, turbulence developed at the top of the sand slope and grains began to flow down the entire front continuously, rather than in a series of slumps or avalanches as when the currents were slow. The final structure developed was a foreset surface that sloped 26 or 27 degrees at the top but decreased to 2 or 3 degrees at the base where it extended outward as the top of a bottomset bed.

Topset beds were developed best where a slight rise in water (sea) level allowed some deposition above as well as in front (seaward) of the previously accumulated sediment (fig. 3). Where water level remained constant, either a very thin wedge of new sediment or none at all formed above and upstream from the foreset slope, where most of the incoming sand accumulated. Where water level was lowered, even slightly, erosion occurred on top of the earlier deposits,

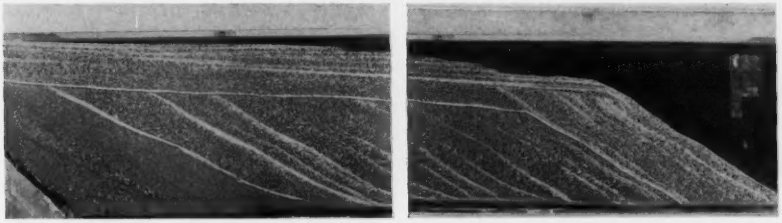

FIG. 3.—Changes in stratification due to lowering and raising of water level. Beveled top of foresets due to lowering water level. Series of topsets due to stages in rising water level.

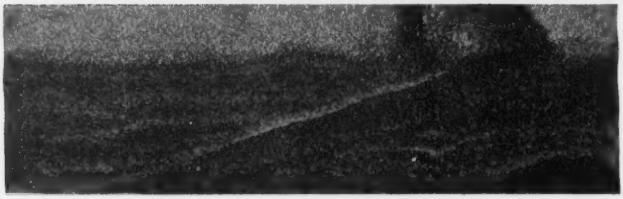

FIG. 4.—Cross-section of multiple delta. Lobe on right built first; overlapping lobe on left built later. Note that strata in lobes are *convex* upward.

and previously formed foresets were beveled or truncated. Thus, in relatively few delta-front strata, as formed in the laboratory, were any well-developed topset beds retained; in most sections only the steeply dipping foreset slopes were preserved.

VERTICAL REPETITION OF FORESETS

With a constant water level in the delta tank, continuing sedimentation can result only in the forward building of sloping foresets, possibly accompanied by bottomsets, which differ from one another only slightly as described in the section on variations in dip of foreset beds in cross-stratification and as illustrated in figure 1. Through this process, a sheet of cross-stratified sand of infinite extent but limited thickness may develop provided no physical restrictions interfere laterally.

Experiments in the laboratory show that a rising water level interrupts the continuity of a forward-building sand sheet and results in a compound or combination structure as seen on a vertical plane. If the water rises slowly, a series of flat-lying beds or topset surfaces develop (fig. 3). If the water rises rapidly to a new level, as shown by Nevin and Trainer (1927), a second set of foreset beds results, duplicating in form the set on which it accumulates. Thus, not only the ultimate shape of the sand body, but also its detailed pattern of stratification are largely determined by changes in water level.

CONVEX-UPWARD STRUCTURES

Experiments in the laboratory delta tank illustrate that, where a sand deposit builds forward as a single sheet with foresets advancing more or less uniformly, vertical sections normal to the direction of movement show stratification that appears as essentially horizontal layers. If, on the other hand, the foward-building sand body consists of two or more lobes, each being fed by a separate stream, strata forming these lobes appear in cross section as curving structures that are convex upward (fig. 4). This type of structure is significant, for it is opposite in orientation to common channel-fill or "festoon" varieties and might easily be mistaken for these in an upside-down position.

CHANNEL-FILL STRUCTURES

Experiments on the development of channel-fill structures have included the cutting

FIG. 5.—Trough cross-stratification formed by filling of channel by stream deposits. Surface of water below channel rims during most of process.

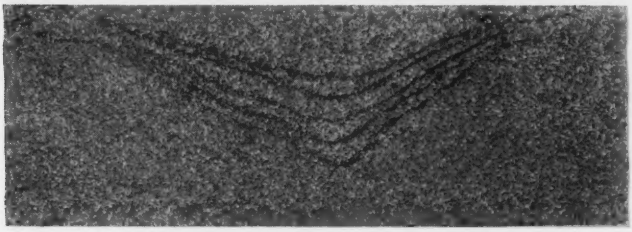

FIG. 6.—Symmetrically-filled channel. Thickening of strata toward bottom of trough. Channel cut by stream and modified by rising water level; filled by submarine current moving down trough.

of channels (1) by streams and (2) by submerged or submarine currents. Channels of the former type tend to be flat bottomed, steep sided to straight walled, and shallow. Those of the latter type are semicircular in section as a result of constant slumping of the walls under water.

The nature of cross-stratification formed by the filling of channels largely depends upon the position of water level. Where a stream deposits sediment in a channel bottom, as the result either of increase in stream load or decrease in stream velocity, the layering tends to be essentially horizontal so that it conforms to the flat-bottomed profile of scour in a stream-cut channel (fig. 5). With higher water level, however, where the channel is completely filled or submerged, deposits develop as curving strata that are concave upward. Thus, varying degrees of curvature result from differences in depth of water in the channel in which deposition occurs.

Where deposition takes place in a submarine channel as the result of longitudinal currents, the strata developed (fig. 6) conform approximately to the channel shape but are not uniform in thickness, for they thin laterally on both sides. In contrast, where deposition is accomplished by sediment dropping from above and settling in quiet water, each stratum is of essentially equal thickness throughout and conforms to the channel shape (fig. 7). Finally, where deposition results from a submarine current passing diagonally over the channel, the filling is asymmetrical (fig. 8).

SUMMARY

Variations in cross-stratification, as reproduced in laboratory experiments conducted so far, include two basic types: (1) those formed on a flat surface by deposition along an advancing sand front, either subaerial or subaqueous (simple and planar cross-stratification of McKee and Weir, 1953), and (2) those formed through the cutting and filling of channels (trough cross-stratification). Within these types, differences in pattern may be classed as major or minor, depending on whether they involve fundamental changes in structural pattern

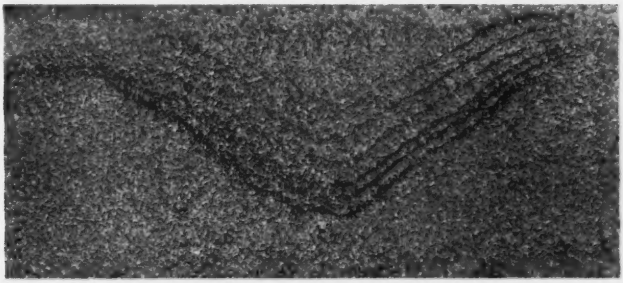

FIG. 7.—Symmetrically-filled channel. Scoured by stream and modified by rising water level. Strata due to settling from above in quiet water.

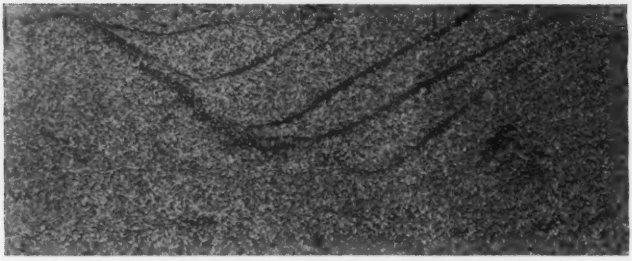

FIG. 8.—Asymmetrically-filled channel. Channel cut by stream and modified by rising water level; filled by submarine current moving in direction diagonal to channel.

or represent only a slight change, as in degree of dip or curvature of stratification surfaces.

Major variations in stratification commonly are the result of fluctuations in water level. A lowering water level normally results in truncation or beveling of earlier deposited cross-strata and removal of topset beds, if present; a rising water level results in compounding of structures or addition of new types, depending on the rate of change. Differences in water level likewise control, to a considerable extent, the curvature and shape of strata filling channels. Thus, analysis of cross-stratification may prove significant not only in determining environments of deposition, but also in interpreting the nature of fluctuations of the depositing medium within an environment.

Minor variations in stratification result from differences in grain size and shape, sorting, speed of water, and other factors. These variations are significant, for they indicate the limits of change within deposits of a particular time. Furthermore, they emphasize the amount of fluctuation within the cumulative deposits of a single environment.

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FIGS. 1–2, JUNE, 1957

COMPARISON OF THE PEBBLES OF THE SHINARUMP AND MOSS BACK MEMBERS OF THE CHINLE FORMATION[1]

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ABSTRACT

Lithology, color, size, sphericity, and roundness of pebbles from the Shinarump and Moss Back Members of the Chinle Formation were analyzed and compared. The difference in the quartz:quartzite:chert ratios of the pebbles, the presence of limestone and siltstone pebbles, and, to a lesser degree, the difference in color of pebbles serve to distinguish the Moss Back from the Shinarump. In areas where the Moss Back and Shinarump are both present, the average ratios of quartz, quartzite, and chert are respectively about 12:37:51 and 82:16:2. Limestone and siltstone pebbles are commonly found in the Moss Back, whereas they are rarely found in the Shinarump. The colors of the Moss Back pebbles are generally darker than those of the Shinarump pebbles. The Moss Back contains more gray to black pebbles and fewer light-colored pebbles, such as red, orange, and white, than the Shinarump. Size, sphericity, and roundness of pebbles do not show a significant difference between the two units.

Fossiliferous pebbles in the Moss Back and Shinarump were derived chiefly from sedimentary rocks of Carboniferous and Permian ages and could have had common sources.

INTRODUCTION

A pebble study of the Shinarump and Moss Back Members of the Chinle formation is being made as part of a detailed stratigraphic study of the Triassic and associated formations of the Colorado Plateau. The detailed stratigraphic study is being made by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

The use of the term "pebble" in this paper denotes the coarse rounded fragments of granule and larger size contained in the conglomeratic units.

The pebble studies are designed to determine whether regional differences exist in composition, size, and varietal ratios of pebbles in conglomeratic units, and to aid in the determination of the source rocks and source directions of the sediments comprising Triassic and associated formations.

Properties used for the comparison of the pebbles of the Shinarump and Moss Back Members of the Chinle Formation are lithology, color, size, sphericity, roundness, and contained fossils. Of these properties, only lithology and color can be used to distinguish the Shinarump from the Moss Back. The fossils contained in the pebbles were identified by Helen Duncan, J. B. Reeside, Jr., Roland W. Brown, Richard Rezak, Lloyd G. Henbest, D. H. Dunkle, Ellis Yochelson, Mackenzie Gordon, Jr., P. E. Cloud, Jr., Jack E. Smedley, and Raymond C. Douglass of the U. S. Geological Survey.

The Shinarump Member of the Chinle Formation was formerly known as the Shinarump Conglomerate. The change from formation to member rank has recently been adopted by the U. S. Geological Survey (Stewart and others, in press).

METHODS OF PEBBLE ANALYSIS

Sampling

The method used to sample the pebbles and the number of pebbles per sample was suggested by Churchill Eisenhart of the U. S. Bureau of Standards. It was suggested that two adjoining rectangles, of a size to enclose at least 150 pebbles each, be marked on the ground and a sample of 150 pebbles be collected from each rectangle.

Data consisting of the lithologic classification of 2 samples of 150 pebbles each from 6 sites were submitted to the Statistical Engineering Laboratory of the National Bureau of Standards. A chi square test, first described by Pearson (1900), was applied to the data from each sample to determine whether the paired samples differed more than might be expected on the basis of random sampling variation. The results obtained for these 6 sites indicate

[1] Publication authorized by the Director, U. S. Geological Survey.

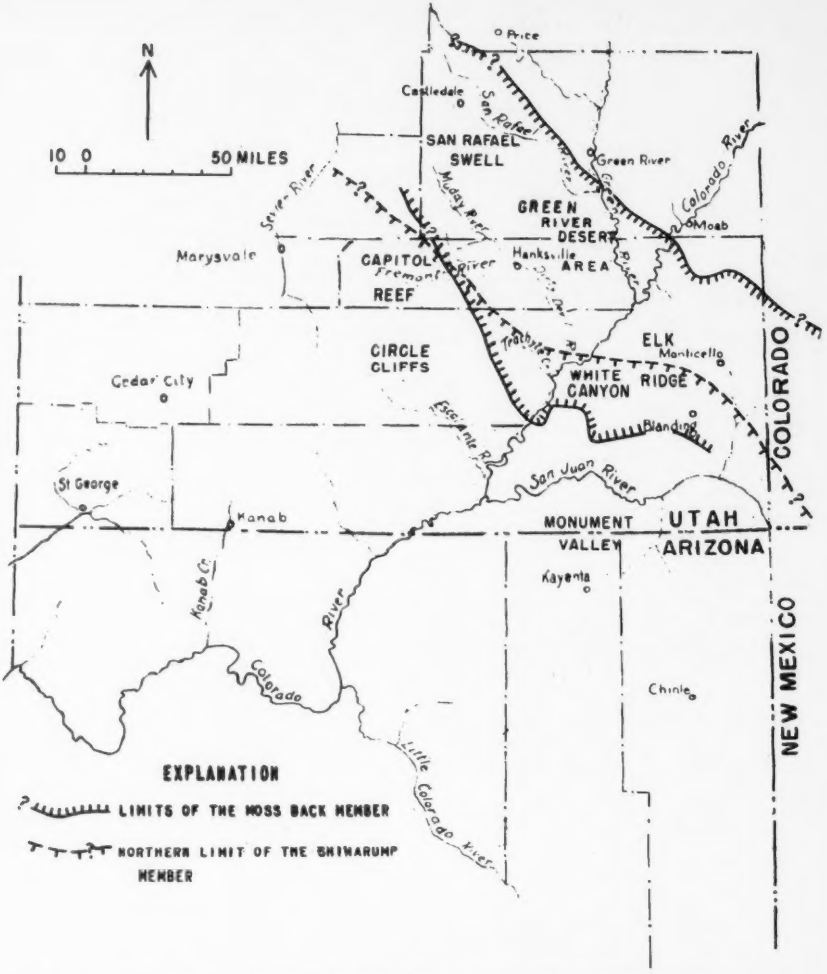

FIG. 1.—Distribution of the Moss Back Member and the northern limit of the Shinarump Member of the Chinle Formation.

that, on the whole, the 2 samples from a site are homogeneous and, therefore, the sampling technique is a satisfactory one. As a result of these conclusions, and to save time, only one sample of 150 pebbles was collected from each site.

Sphericity and Roundness

Wadell (1932) defined roundness and sphericity and was the first to show that these terms were not synonymous. For practical purposes, the index of roundness can be expressed as a ratio of the curvature of the corners and edges of a pebble to the curvature of a circle inscribed within the projection plane of that pebble. The sphericity of a pebble is defined as the ratio of the surface area of a sphere having the same volume as the pebble to the surface area of the pebble.

Krumbein (1941a) has devised rapid methods to determine roundness and sphericity; these methods give results within 5% of Wadell's methods. For roundness, a pebble is compared with standard images of known roundness, and a roundness value is assigned to the pebble. Sphericity is determined from ratios of the length of the a-, b-, and c-axes, or the long, intermediate, and short diameters of the pebbles; the diameters do not necessarily intersect but must be mutually perpendicular. Two ratios, b/a and c/b, from each pebble are determined and located on the axes of a chart given by Krumbein (1941a, fig. 5) from which sphericity can be read directly.

Size

Two measures of pebble size are used for comparative purposes; these are the length of the longest pebble that can be found at each collection site, and the mean intermediate diameter of all pebbles at the collection site.

Lithology and Color

Each pebble is broken to determine the lithology. Composition of the quartzose-pebble assemblage is expressed in terms of the relative amounts of quartz, quartzite, and chert. The color of the fresh surface is compared with colors in the National Research Council Rock Color Chart (Goddard and others, 1948). The color is recorded by the color chart symbol which permits a quantitative comparison of samples.

GEOLOGIC RELATIONSHIP OF THE SHINARUMP AND MOSS BACK MEMBERS OF THE CHINLE FORMATION

The Shinarump Member of the Chinle Formation crops out over large areas in northern Arizona and southern Utah, and less extensively in northwestern New Mexico and southeastern Nevada (fig. 1). It has a maximum thickness of about 250 feet, but at many places in southeastern Utah it is absent, and siltstone and claystone of the Chinle rest on the Moenkopi Formation. The Shinarump Member commonly weathers to form a prominent ledge or vertical cliff. It is generally a grayish- to pale yellowish-orange medium- to coarse-grained sandstone composed of subround clear quartz grains. Conglomerate and conglomeratic sandstone are common. The pebbles are composed almost entirely of quartz, quartzite, and chert, but the proportions of these types differ greatly from area to area.

The Moss Back Member of the Chinle Formation crops out in parts of central and southwestern Utah and probably in a small area in western Colorado (fig. 1). It is a yellowish-gray and very pale orange fine- to medium-grained well-sorted sandstone composed of subround clear quartz grains. Lenses of conglomerate and conglomeratic sandstone are common. The Moss Back typically weathers to form a vertical cliff.

Parts of Elk Ridge and White Canyon, Utah, are the only areas in which both the Moss Back and Shinarump crop out.

In the White Canyon area, Utah, the Triassic section, in ascending order, consists of the Moenkopi Formation, the Chinle Formation, and the Wingate Sandstone. The Moss Back member lies about 200 feet above the Shinarump Member (fig. 2). North of White Canyon the Shinarump pinches out and the Moss Back is closer to the base of the Chinle. About 15 miles north of White Canyon the Moss Back is at the base of the Chinle.

Pebbles in the Shinarump Member of the Chinle Formation

Pebble samples were taken in the Shinarump, where exposures permitted, from the Kanab area, Utah, to the White Canyon area, Utah. The quartz:quartzite:chert ratio in the Shinarump, which is about 11:46:43 in the Kanab area, changes to about 82:16:2 in the White Canyon area (table 1).

The colors of quartz, quartzite, and chert differ markedly among the areas sampled. In general in the Kanab area, 10 to 30% of the pebbles in the Shinarump have bright colors such as red, pink, or orange. In the White Canyon area, however, over 90% of the pebbles are mostly of light colors such as white, gray, and tan.

The maximum length of pebbles, determined by measurements of the long axes, varies regionally (table 1). The maximum length decreases from about 113 mm in the Kanab area to about 38 mm in the Circle Cliffs area, and decreases from about 125

mm in the southeastern part to about 40 mm in the northwestern part of the White Canyon area.

The mean size of the pebbles, determined by measurements of the intermediate axes, reflects a decrease in size over the same area as the maximum size pebbles—that is, a general decrease in size from south to north (table 1). The mean size decreases from 23 mm in the Kanab area to 13 mm in the Circle Cliffs area and from 25 mm in the southeastern part to 12 mm in the northwestern part of the White Canyon area.

The pebbles in the White Canyon area have the highest average index of sphericity (0.77) and are composed mainly of quartz. The pebbles in the Circle Cliffs area are composed largely of quartz and quartzite and the average index of sphericity is about 0.75. In the Kanab area the pebbles are composed largely of chert and quartzite and the average index of sphericity is lowest—about 0.72.

The average roundness of the pebbles is highest—about 0.62—in the White Canyon area. The average roundness is 0.59 in the Kanab area and 0.58 in the Circle Cliffs area.

The largest average indices of both sphericity and roundness are in the White Canyon area where the pebbles are composed mainly of quartz. It is not known if the high quartz-pebble content is the cause of the high roundness and sphericity figures, but such a correlation does seem possible. Of two samples from the Circle Cliffs area that are high in quartz, one sample has a high average index of roundness; the other has the lowest of all samples taken. Both samples have a high average index of sphericity, and of these, the one that has the highest sphericity has the lowest roundness. Such apparent anomalies indicate that generalizations about differences in sphericity or roundness should be confined to differences between the mean of all samples in an area and the mean of samples from other areas, and not differences between individual samples. Pebble lithologies are different from area to area, and this has a great influence on the shapes of pebbles. The lithology of a pebble strongly controls its original shape, cleavage or bedding, and durability, and these factors influence the shape of the pebble.

Pebbles in the Moss Back Member of the Chinle Formation

Conglomerate and conglomeratic sandstone are common in the Moss Back Member. The pebbles comprise two lithlogic assemblages: (1) quartz, quartzite, and chert; and (2) limestone and siltstone. These assemblages occur together and separately, but are commonly present in the same lens

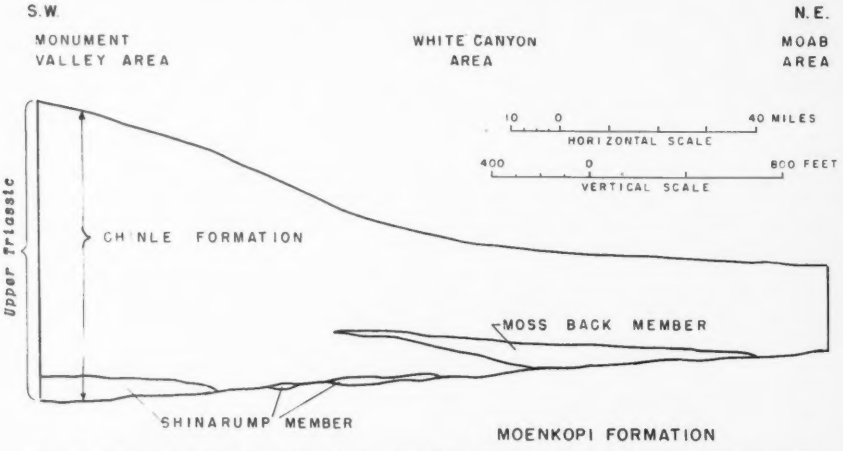

FIG. 2.—Generalized stratigraphic relationship of the Shinarump and Moss Back Members of the Chinle Formation.

TABLE 1.—*Location of sample sites and the composition, size, roundness, and sphericity of pebbles from each site*

Location	Sample No.	Composition (Percent)			Maximum Length (mm)	Mean Size (mm)	Roundness Index	Sphericity Index
		Quartz	Quartzite	Chert				
Moss Back Member of the Chinle Formation								
Elk Ridge area								
Deer Flat	HA-40	9	48	43	70	17	0.62	0.74
The Notch	HA-134	20	46	34	83	22	0.62	0.76
Bridger Jack	HA-132	6	18	76	80	19	0.58	0.75
Average		12	37	51	78	19	0.61	0.75
Green River Desert area								
Poison Springs Box Canyon	HA-61	9	28	63	70	20	0.61	0.74
Junction Butte	HA-102	12	28	60	75	22	0.63	0.75
"C" group mines	HA-129	8	33	59	95	21	0.58	0.74
Bighorn Mesa	HA-128	9	49	42	58	23	0.60	0.73
Middle Trail	HA-120	13	48	39	75	20	0.58	0.74
Average		10	37	53	75	21	0.60	0.74
San Rafael area								
Muddy River	HA-46	13	26	63	60	17	0.57	0.75
Chute Canyon	HA-57	9	31	60	58	18	0.61	0.76
Straight Wash	HA-79	21	61	18	85	16	0.61	0.74
Buckhorn Wash	HA-91	16	65	19	100	23	0.62	0.74
Average		15	46	40	76	19	0.60	0.74
Shinarump Member of the Chinle Formation								
Kanab area								
Canaan Gap	HA-2	18	34	48	113	20	0.61	0.69
Pipe Springs	HA-3	5	39	56	93	22	0.59	0.70
Fredonia	HA-1	6	49	45	113	23	0.55	0.74
Pioneer Gap	HA-4	15	60	24	93	22	0.61	0.73
Average		11	46	43	103	22	0.59	0.72
Circle Cliffs area								
Colt Mesa	HA-5	45	24	31	45	16	0.57	0.74
The Peaks	HA-6	79	12	9	58	15	0.49	0.79
Lampstand	HA-7	40	18	42	63	15	0.54	0.74
Bicknell	HA-8	30	54	16	45	14	0.65	0.74
Twin Rocks	HA-17	67	18	15	38	13	0.64	0.75
Average		52	25	23	50	15	0.58	0.75
White Canyon area								
Happy Jack	HA-13	79	17	4	40	12	0.59	0.79
Soldiers Grave	HA-21	92	6	2	63	19	0.60	0.75
Frey Canyon	HA-14	96	4	0	80	26	0.65	0.79
Dillon mine	HA-42	79	21	0	97	25	0.63	0.76
Posey mine	HA-10	60	34	5	85	19	0.63	0.78
Red House Spring	HA-11	86	9	5	125	25	0.62	0.77
Clay Hills Pass	HA-12	71	28	1	58	22	0.63	0.76
Deer Flat	HA-38	90	10	0	85	24	0.62	0.75
Average		82	16	2	79	22	0.62	0.77

along an outcrop. Where the limestone and siltstone pebbles occur with the quartzose pebbles, they generally are 10 to 20 times as numerous as the quartzose pebbles. Where only limestone and siltstone pebbles are present, they may constitute more than 50% of the rock by volume.

The limestone and siltstone pebbles are

not counted with the quartz, quartzite, and chert pebbles, but a visual estimate was made of their quantity. They will not break out of the matrix, but are easily identified by the weathered surface characteristic of these rocks.

The average ratio of quartz:quartzite:chert pebbles in the samples from the Moss Back Member is 12:40:48. These figures were obtained from a study of 3000 pebbles collected at 12 localities (table 1). The ratios are not greatly different from locality to locality. At places, the difference may be greater between samples within an area than between samples from different areas.

At all places studied, quartz pebbles constitute a minor part of the conglomerate in the Moss Back Member. Quartz pebbles comprise about 12% of the total quartzose pebbles in the Elk Ridge area, about 10% in the Green River desert area, and about 15% in the San Rafael Swell area; quartzite and chert comprise most of the remainder in about equal proportions.

The colors of pebbles are not appreciably different in the areas of outcrop. Some of the chert pebbles have bright colors, but in general the pebbles are mostly shades of gray to black.

The maximum length of the pebbles ranges from 58 to 100 mm, but this range in maximum length does not show a systematic regional variation. The mean size of the pebbles ranges from 16 to 23 mm and is about the same throughout the Moss Back Member. This variation, similar to the variation of maximum length, is not systematic regionally; both the maximum and minimum mean sizes obtained were on samples from the San Rafael Swell.

Sphericity and roundness figures vary little over the entire area of outcrop. The sphericity averages about 0.74 and ranges from 0.73 to 0.76. The roundness averages about 0.60 and ranges from 0.57 to 0.62. The differences in sphericity and roundness are small and show no systematic changes in any direction across the area.

Comparison of Pebbles in the Shinarump and Moss Back Members of the Chinle Formation

In the Kanab, Utah, area the quartz:quartzite:chert ratio of the Shinarump is about the same as that of the Moss Back in the areas to the northeast (table 1). This is the only area studied, however, where the Shinarump has such a similarity to the Moss Back in this regard. It is about 100 miles from the nearest Moss Back outcrop.

The lithology of the quartzose pebbles of the Shinarump and the Moss Back are similar in that quartz, quartzite, and chert are present in both units. The differences between the two units are only in the colors and ratios of the three components. In the White Canyon and Elk Ridge areas where the Moss Back and Shinarump Members both crop out, the quartz:quartzite:chert ratios are 82:16:2 for the Shinarump and 12:37:51 for the Moss Back. From an average of all the samples studied the ratios are 55:27:18 for the Shinarump and 12:40:48 for the Moss Back. The most obvious difference is the percentage of quartz pebbles in each unit. The percentage of quartz in the Moss Back is persistently low, whereas it is high in the Shinarump.

A primary difference in the lithologies of the Moss Back and the Shinarump is that the Moss Back contains limestone and siltstone pebbles, whereas the Shinarump does not.

Five hundred pebbles from each unit have been compared with colors in the National Research Council Rock Color Chart (Goddard and others, 1948). The colors of the pebbles from both units fall into the same categories of the color chart. Close observation, however, shows that the ratio of gray to black pebbles is greater in the Moss Back, and this difference is great enough to be seen at the outcrops.

The maximum length and the mean size of pebbles are not significantly different between the two units. Locally the pebble sizes are different, but regionally the sizes are nearly the same.

The means of the indices of sphericity and roundness of the quartz, quartzite, and chert pebbles are essentially the same for each unit, although fewer determinations were made on Moss Back samples. The mean was determined from all quartzose pebbles in the samples.

The pebbles in both units have reached "maturity" as defined by Plumley (1948)

in his study of sediment transport in the Black Hills region. Three indices of maturity that Plumley cites are: (1) essentially all pebbles are quartzose (that is, quartz, quartzite, or chert), (2) high index of roundness, and (3) high index of sphericity.

Pebble-size components in the units studied are not all quartzose; limestone and siltstone pebbles are present in the Moss Back Member. The two types of pebbles may be together or separate, and either may overlie the other. Moreover, the limestone and siltstone pebbles are chemically and mechanically unstable. If they had been introduced into the sediments from the same source area as the quartzose components, a reduction in the ratio of soft rock components to quartzose components would be evident across the sampled area. Such is not the case; regionally, the ratio of soft rock to quartzose components and the size of the soft rock components are about the same.

Plumley's data (1948) suggest that indices of maturity are reached rather quickly in gravel deposits. From a study on Rapid Creek in the Black Hills, he found that 30 miles of transport resulted in the loss of all but 2 or 3% of the limestone and sandstone components that had originally comprised about 25% of the gravel.

Krumbein (1941b), in an experiment on the effects of abrasion on the size, shape, and roundness of rock fragments, showed that for limestone fragments, after the equivalent of 20 miles of transport in a tumbling barrel, the roundness seemed to approach an asymptote slightly higher than 0.64 and the sphericity seemed to approach an asymptote slightly higher than 0.77. The limestone was obtained from a commercial crusher, which assured a high initial angularity in the fragments. The initial average roundness was 0.13 and the initial average sphericity was 0.65. This shows that roundness had increased nearly 400%, whereas sphericity had increased only about 18%.

The average sphericity of both the Shinarump and Moss Back pebbles is 0.75 and the average roundness is 0.60. The indices are lower than the end figures in Krumbein's experiment. This can be accounted for by the homogeneity of Krumbein's samples, whereas the Shinarump and Moss Back samples are composed of three different rock types.

The quartzose pebbles of the Shinarump and Moss Back are regarded as having attained maturity. The area across which the pebbles were sampled is well over 100 miles long. In this distance the indices of roundness and sphericity change very little, which indicates an asymptotic value had been approached prior to deposition in the area being studied.

Fossils in the Pebbles of the Shinarump and Moss Back

Some of the fossils found in the Shinarump and Moss Back are indigenous to these units, but most of them are contained in the pebbles. The only fossils indigenous to the Shinarump and Moss Back, found in this study, are wood, other plant remains, and phytosaurian bones.

Most of the fossils found are contained in pebbles of chert. Some of the fossiliferous pebbles in both units apparently were derived from the Kaibab Limestone of Permian age or rocks of the same age as the Kaibab. Others contain fossils that are known to occur in the Rico, Hermosa, and Redwall Formations, suggesting these formations as possible sources. One sample contained bryozoans commonly found in the Brazer Limestone of Mississippian age and its equivalents. Other samples contained a genus of algae that is known only from the Permian. In western North America this algae has been reported from the Carlsbad Group, the Capitan Limestone, and the Delaware Mountain Group of New Mexico and Texas.

From the lists of fossils found in the pebbles it is evident that rocks of several ages and of different areas contributed pebbles. The lists include bryozoans, protozoans, brachiopods, pelecypods, algae, and horn corals. Some of the genera were identified in pebbles that were collected from both the Shinarump and Moss Back. Other forms are known in pebbles only from one unit or the other. Fossils, however, that so far are known in pebbles of only one unit cannot be considered indicative of that unit. Inadequate sampling alone could account for an assemblage of fossils found in one unit and not found in the other.

SUMMARY

Differences in the pebbles of the Shinarump and the Moss Back members can be used to distinguish the units. These differences are mainly: (1) limestone and siltstone pebbles abundant in the Moss Back and essentially absent in the Shinarump, (2) a large percentage of quartz pebbles in the Shinarump and a low percentage in the Moss Back, and (3) the ratio of gray to black pebbles is greater in the Moss Back than in the Shinarump.

Sphericity and roundness vary only slightly and are about the same for each unit, suggesting that the pebbles are mature. The average indices of sphericity and roundness are respectively about 0.75 and 0.60.

The fossils contained in the pebbles cannot now be used to identify either the Shinarump Member or Moss Back Member. With further work, however, it is hoped that fossils will aid in locating source rocks.

The differences between the pebbles of the Moss Back and Shinarump are significant. Each probably received major contributions from different source areas. Part of the Shinarump Member probably received a major contribution from a granitic area, as evidenced by the high quartz-pebble content, that did not contribute or was only a minor contributor to the Moss Back Member. The Moss Back Member, on the other hand, has a high content of limestone and siltstone pebbles that must have been locally derived, probably from the underlying sedimentary rocks.

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FIGS. 1–3, JUNE, 1957

BEACH EROSION AND CONCENTRATION OF HEAVY MINERAL SANDS

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ABSTRACT

The east coast of India, extending from Vasishta Godavari river in the south to Vamsadhara river in the north was surveyed with special reference to the beach configuration and concentration of heavy mineral sands. It was found that storms in the Bay of Bengal and the annual changes in sea level cause beach erosion, while large scale regression of the beach is the result of changes in the oceanographic environment. The concentration of well-sorted heavy mineral sands is effected by such beach erosion and beach regression. This is believed to be due to the sorting action of the powerful waves responsible for the erosion and the transporting action of the along-shore currents.

INTRODUCTION

The wide range and sudden changes observed in the processes of deposition, sorting, and concentration of heavy mineral sands occurring along the east coast of India form an interesting study. The economic importance of the concentrates of heavy minerals like ilmenite, monazite etc., has added emphasis to the study. Work has been carried out on the origin and economic aspects of the heavy mineral sands of the Visakhapatnam beach, India, by Mahadevan and Srirama Das (1948), Mahadevan and Sathapathi (1948), and Srirama Das (1951). Recent studies include investigations of short period variations in the heavy minerals of the Visakhapatnam beach (La Fond and Prasada Rao, 1954) and the effect of high waves on the heavy mineral sands (Mahadevan and Srirama Das, 1954). The nature of deposition, sorting, and concentration of heavy minerals at the mouths of some rivers along the east coast is taken up by the author in collaboration with E. C. La Fond, and the processes responsible for the unilateral distribution of the heavy minerals near the river mouths are explained (Borreswara Rao and La Fond, 1956).

In the coarse of further studies, beach erosion and beach regression phenomena, which are discussed in this paper, have been found to play a significant role in effecting the well-sorted concentration of heavy minerals.

EVIDENCE

Beach erosion and beach regression phenomena are especially apparent in the following localities along the east coast: (1) the coastal strip west of Vasishta Godavari confluence, (2) the coast east of Vasishta Godavari, (3) the coastal strip north of Gautami Godavari, (4) the Visakhapatnam coast, and (5) the coastal area north of Nagavali confluence (fig. 1). Periodical surveys of sand level and mineral concentration in these areas were undertaken in order to study the changes in beach configuration and heavy mineral concentration.

1. *Coast west of Vasishta Godavari.*—A survey of the coastal strip west of Vasishta Godavari river mouth during two different periods, April and the following January, shows from the following evidence that erosion of the beach resulted in a better sorting and concentration of heavy mineral sands. A comparison of the April and January surveys shows that:

a. the wide backshore in the first survey had narrowed down by the time of second survey;

b. hard and compact clay, forming the foreshore near low-tide level, and a sand bar in the off-shore region were exposed at the time of the second survey;

c. the sea cut across the beach into the backwater region about two miles west of the river mouth, forming a fresh tidal flow, a phenomenon not present at the time of the first survey;

d. there was a thick surface concentration of well-sorted heavy minerals in the backshore, particularly near the foot of the berm, in the second survey, in contrast to thin layers at the time of the first survey.

2. *East of Vasishta Godavari.*—The beach had undergone regression, probably in 1951, when Pandila, a coastal village, was completely submerged leaving only the half-submerged Obelisk Beacon standing as evidence. At present a rich concentration of heavy mineral sands is noticed over a wide area. Patches of hard and compact clayey foreshore are exposed near the low-tide level.

3. *North of Gautami Godavari confluence.*—The ruins of the Masanatippa village, the half-destroyed Bhairavaswami temple and the submerged forest, exposed during the low-tide period, are the excellent evidences of beach regression to be found north of the Gautami Godavari confluence (fig. 2). The foreshore, as well as backshore, of this beach shows deposits of heavy mineral sands.

4. *Visakhapatnam coast.*—Beach erosion was considerable during December 1951, probably due to a storm in the Bay of Bengal at that period. Immediately after the storm, the heavy mineral sands were found to be sorted and concentrated in several patches. An account is given by Mahadevan and Srirama Das (1954). Similar phenomena on the beach north of Lower Kausika Drain, resulting from the November 1955 storm, were observed by the author.

5. *Coastal area north of Nagavali confluence.*—Beach erosion due to the changes in sea level is noticed along the coastal strip about a mile north of Nagavali confluence.

Sand level and mineral concentration

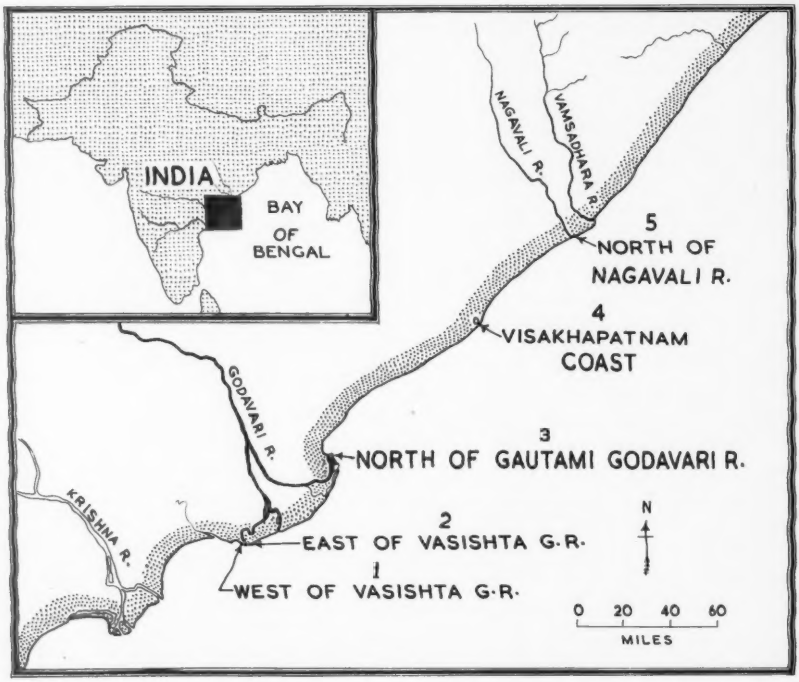

FIG. 1.—Location of coastal areas where beach erosion and concentration of heavy minerals were observed; *Inset:—Map of India showing the general location of the area along east coast.*

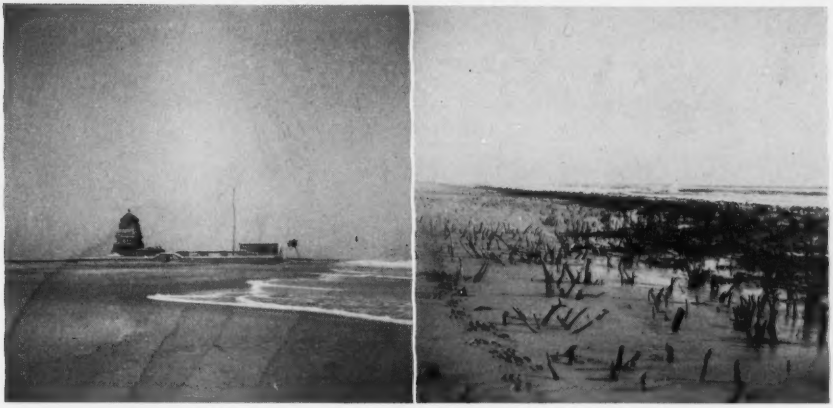

FIG. 2.—Evidences for beach regression north of Gautami Godavari confluence.

surveys of this area at different periods during February 1955 and January 1956 have shown that the high backshore region formerly exposed during February-March 1955 (period of minimum sea level position) has been eroded during August-September 1955 (period of maximum sea level position) to a low and gently sloping beach. The entire process constitutes one annual cycle of sea level changes which in this region is more than 2 feet.

CONCENTRATION OF HEAVY MINERALS ALONG EAST COAST OF INDIA

Heavy mineral sands occurring along the east coast of India enter the sea as a result of two major processes: (1) the drainage system of the area and (2) the coastal erosion. The minerals so introduced are sorted by the churning action of waves coupled with the transporting action of currents, as well as by the panning action of the swash and backwash on the beach. Much of this river-transported material is deposited near the river mouths. Light minerals are carried off-shore or farther along the beach, while the heavy minerals remain. Material that escapes sorting is carried along with the lighter minerals for deposition as mixed sand along the beach or in the off-shore region. The off-shore deposit is later added to the beach by the slow onward creep of sand during periods of low waves (Mahadevan and Anjaneyulu, 1954). This mixture of heavy and light minerals is a secondary source from which rich concentrates can be derived by later beach erosion and beach regression.

High waves produced during stormy weather erode a considerable part of the backshore, developing vertical scarps near high tide level. The eroded material of mixed sand is kept in suspension by the agitated sea. During this period the panning action of the waves causes sorting. This is especially true where a hard and compact clayey layer underlies the sandy beach, acting as a panning vessel. The lighter minerals are carried along with the backwash for deposition at a lower level along the beach (Mahadevan and Srirama Das, 1954) or are in some cases even transported further up the beach. The heavy minerals are left behind, forming thick, well-sorted residual concentrates on the backshore near the foot of the berm (fig. 3a).

A second factor causing beach erosion is a change in sea level. The water level changes from time to time during the course of a single day, and from month to month during the year. It reaches a maximum in the period of August-September, which is the period of N.E. monsoon, and is at a minimum in February-May.

When the sea attains a maximum level high and powerful waves constantly act on the submerged backshore. The waves pan and sort out light and heavy minerals

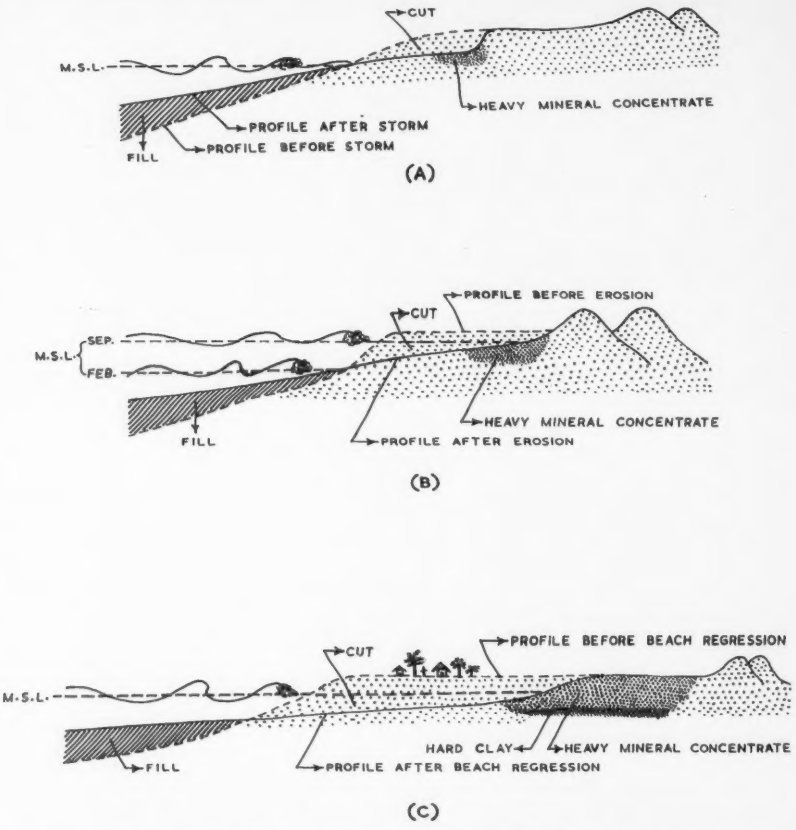

FIG. 3.—Schematic representation of the effects of (A) Storms, (B) Sea level changes and (C) Large scale beach regression, on the beach profile and concentration of heavy mineral sands.

which are inaccessible during periods of low sea level. Here too, an underlying layer of hard and compact clay facilitates better panning. When the sea level reaches its original lower position, the lighter minerals have been carried off-shore, while the heavy fractions are left on the backshore near the high tide line (fig. 3b).

A change in the oceanographic environment sometimes brings about a permanent change in shoreline, a typical example of which is the regression of the beach near the confluence of Vasishta Godavari. La Fond and Prasada Rao (1956) believe that lack of a normal sand supply from the south, combined with the erosive action of the north-flowing current, has caused a permanent change in the beach configuration near Uppada, a village about seventy miles south of Visakhapatnam. These permanent changes result in sorting of the mixed sand on the retrograded beach. During the period of beach regression, the mixed sand is sorted, first by the waves and later by swash and backwash. The difference in the velocities of swash and backwash facilitates selective deposition of heavier minerals near the swash line, while the lighter minerals are carried away (Evans, 1939). Bars are developed by the off-shore deposition

of light minerals and by along-shore current which is especially strong along the east coast.

With progressive advancement of the sea shoreward, sorting becomes progressively better, due to the repeated action of the waves, swash, and backwash (fig. 3c).

SUMMARY AND CONCLUSIONS

A systematic study with special reference to the beach configuration and distribution of heavy mineral concentrates was carried out on the east coast of India, from Vasishta Godavari in the south to Vamsadhara river in the north.

Beach erosion and beach regression were found to play a significant role in effecting the concentration of well-sorted heavy mineral sands. In view of the academic and economic importance of the problem, the present study should be extended to other regions of the coastal area.

The systematic study of the heavy mineral concentrates leads to an appreciation of the beach configuration and to problems relating to coast-line development, which are of prime importance in controlling beach erosion.

ACKNOWLEDGMENTS

The author expresses his grateful thanks to Professor E. C. La Fond, Visiting Professor of Oceanography in Andhra University, for his interest and constant help in the work, and to Professor C. Mahadevan, for providing the opportunity and facilities for carrying out this study.

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FIGS. 1–4, JUNE, 1957

HEAVY MINERAL STUDIES IN TILLS OF ONTARIO AND ADJACENT AREAS

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ABSTRACT

Investigations of heavy minerals in tills peripheral to the Canadian Shield indicate the following characteristics: the Grenville tills contain more garnets, tremolite-actinolite, and hypersthene than the Superior tills, which are richer in chlorite-serpentine, clinopyroxenes, and epidotes. Epidotes dominate in some Superior tills northwest of Lake Superior. Hornblende is very abundant in all tills, but particularly along the Grenville-Superior boundary north of Lake Huron.

The Huron lobe tills contain more heavy minerals than the Erie tills. The heavy mineral content in the Huron tills of southwestern Ontario derive principally from the Superior province, with some admixture from the west end of the Grenville, while typical Grenville minerals dominate in the Erie tills.

Comparison of heavy mineral content between successive tills and recessional moraines reveal a shifting of ice flow in both lobal areas during Wisconsin time. First each lobe entered its lake depression from north-northeast. Later the major flows drifted apart, the Huron lobe assuming a more north-south, and the Ontario-Erie lobe, a northeast-southwesterly direction. The space between them became occupied by minor but tributary ice-flows.

INTRODUCTION

Studies of Pleistocene deposits of southwestern Ontario by Taylor (1913) and Chapman and Putnam (1951) have indicated the existence of several ice lobes during late Wisconsin time.

Exposures along the Thames River and excavations at Fanshawe Dam near London, in the heart of southwestern Ontario, reveal the existence of up to five till beds. No interglacial deposits have been found between them. Till fabric studies by Dreimanis lead to the conclusion that these till beds were deposited by alternating advances of glacial lobes from the northwest, northeast and southeast.

This complicated history of Wisconsin time in the London area could be deciphered if petrographic composition and texture of tills of each glacial lobe were known. Because the principal lobes retreated from the London area towards the Lake Huron and Lake Erie depressions, leaving recessional moraines, till samples for petrographic studies were collected from these moraines or the till plains immediately behind them. The Huron ice lobe formed the following moraines while retreating from London (see fig. 1): Mitchell, Lucan, Seaforth, Wyoming (correlated with the Port Huron moraine in Michigan). The Erie-Ontario lobe left at least seven moraines southeast of London: Ingersoll, Westminster St. Thomas, Norwich, Tillsonburg, Paris, Galt (see Chapman and Putnam, 1951, p. 29–31 for a description of the glacial retreat).

Two more lobes may have reached southward as far as the London area: the Georgian Bay lobe and another one, which came across the Haliburton district and Lake Simcoe and, therfore, may be called the Haliburton-Lake Simcoe Lobe. Since the surface deposits of these lobes are outside of the London area, they were excluded from the first stage of this lobate study, though future plans require their investigation.

Both the Huron and Erie-Ontario ice lobes have traversed Paleozoic and Precambrian terrains. The Paleozoic rocks of both lobate areas are of similar composition: limestones, dolomites, shales, and some sandstones. The more distant Precambrian rocks show a greater variety and, when found in the drift of southwest Ontario, are easily distinguishable from local Paleozoic sediments. Therefore, Precambrian materials seem to be more suitable for differentiation of the lobes named. In order to avoid working with bulky till samples, to increase the number of observations, and to cover a larger area, *heavy minerals* were selected as the principal object of this study.

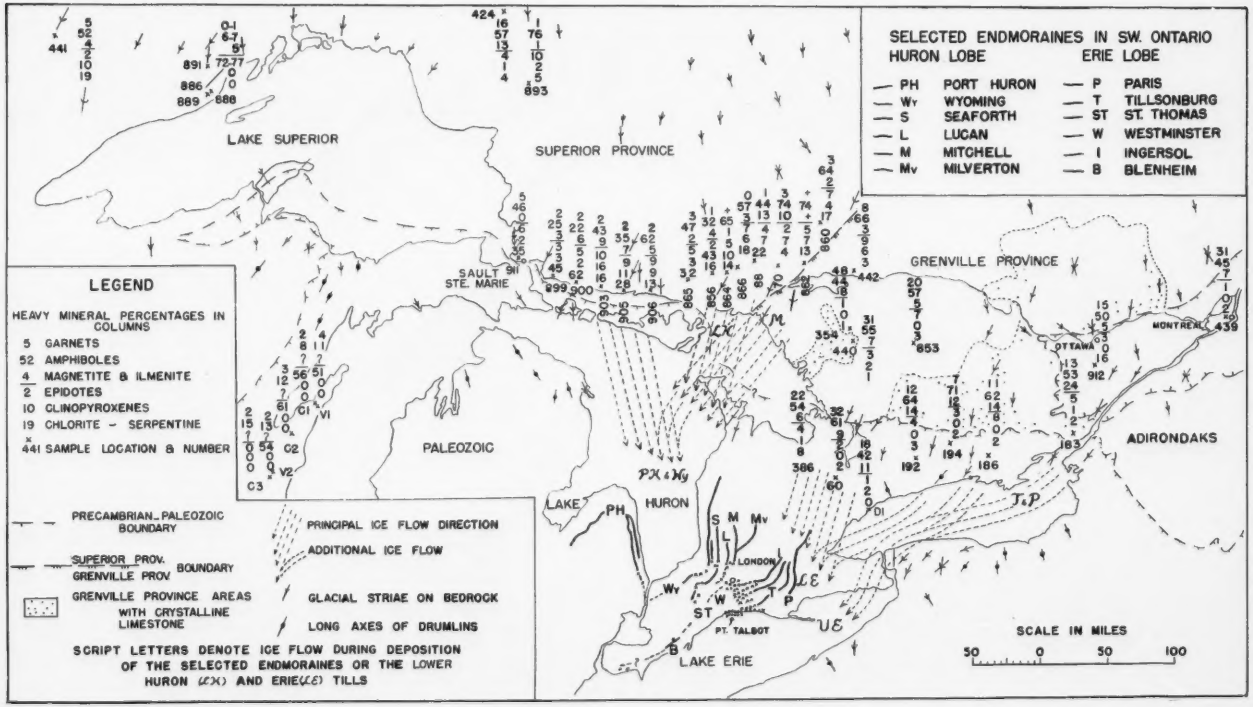

FIG. 1.—The Great Lakes region protraying the principal geologic areas, till sample locations, and heavy mineral results. (C1, C2, C3, V1, V2, from Murray, 1953, p. 147, and D1 from Derry, 1933, p. 114, first boulder clay; UE, ice flow during deposition of the upper Erie till).

Studies of Precambrian rocks in the Lake Superior region by Tyler, Marsden, Grout, and Thiel (1940) and of crystalline material in the drift of southern Ontario by Gravenor (1951, p. 67) indicate that igneous rocks are relatively rich in heavy minerals; their amount is usually between 7 and 20%. Metamorphic sediments of the Lake Superior region contain less heavy minerals; in most cases .5–1%, more in the Oronto group—average 7.4% (see Tyler, Marsden, Grout and Thiel, 1940).

Heavy minerals are absent, or present in very small quantities, in limestones, dolomites, and fine-grained shales, the dominant sedimentary Paleozoics of southern Ontario (Derry, 1934, p. 84 and Holstein, 1936). Sandstones or sandy lenses in the above sediments contain varying amounts of heavy minerals, but these rocks are of minor importance in southern Ontario. Therefore, most of heavy detritals found in the tills of Ontario must have been derived from Precambrian rocks. Though they may have been picked up from Ordovician rocks marginal to the Canadian Shield, their ultimate source was the Precambrian. Derry (1934, p. 87) has found on Manitoulin Island that Ordovician rocks contain local Precambrian detritals, such as hornblende and garnet. Those Ordovician and Silurian rocks deposited further south in southern Ontario contain completely different suites of heavy minerals, zircon, leucoxene, collophane, iron sulphides, tourmaline being dominant (D. R. Derry, 1934, p. 84–88 and A. Holstein, 1936). Since tills of southwestern Ontario either do not contain these minerals or carry very low amounts of them (except for authigenic iron sulphides), it seems reasonable to conclude that heavy minerals (except as noted above) found in the tills of southwestern Ontario, are derived principally from Precambrian rocks of the Canadian Shield. Kruger (1937) has reached similar conclusions for Minnesota tills, and Gravenor (1951, p. 66–67) has even used the percentage of heavy minerals as a criterion in determining the amount of crystalline material in till.

Steps of Investigation

This study constitutes a part of a larger project of Pleistocene research relative to S. W. Ontario (see Dreimanis and Reavely, 1952). The first step was to investigate whether heavy minerals differ qualitatively and quantitatively in tills from the Huron and the Erie-Ontario lobes. A positive answer resulted from Cook's M.Sc. thesis (1952), based upon heavy mineral analyses of 92 till samples from Ontario and Michigan. Knox (1952) tried to differentiate the lower from the upper till of the Erie-Ontario lobe by applying heavy mineral studies of 29 till samples as one method. Cook (1952) also began to study tills from Precambrian source areas (13 samples), and Moretti (1954) continued this work, investigating heavy minerals from 16 additional samples (plus some others, analyzed after completion of his thesis). Most till samples and field observations were gathered by Dreimanis, but credit is also due to Dr. E. P. Henderson, Dr. J. A. Elson and Dr. V. K. Prest for supplying us with additional samples. The heavy mineral studies were guided and supervised by Reavely. Dreimanis did the final interpretation of the results of investigations.

This study was made possible by grants from the Ontario Research Council from 1950 to 1954, and from the Geological Survey of Canada 1955–56.

Till Samples from the Precambrian Area

Heavy minerals were studied in 33 samples from the periphery of the Precambrian shield in Ontario and Quebec or immediately south of its southern boundary. Most of them were gathered between Sault Ste. Marie and Montreal, because this was considered to be the most probable area traversed by both the Huron and Erie-Ontario ice lobes. Some samples were taken also from the Lake Superior area (fig. 1).

It is usually assumed that fragments of local bedrock dominate in till. Crushing of relatively resistant Precambrian rocks down to the sand grain-size, which was investigated for heavy minerals, requires transport by a glacier for some distance. Gravenor (1951, p. 69) has found south of the Precambrian boundary in southern Ontario, that till contains 45% of crystalline material 29 miles south of that boundary and still 25–30% at a distance of 55–68 miles. Therefore, it seems reasonable that most of the heavy minerals found in tills from the Precambrian area would have been gathered

from an extensive strip of bedrock underlying the glacial flow. The authors realize that till samples had to be taken at regular close intervals along several trends across the ice flow direction, but means were not available for systematic sampling in this manner. Therefore, intervals between sample locations vary considerably. The writers consider this study merely as a preliminary survey with the hope that it will stimulate further interest in investigation of heavy minerals for regional studies of Pleistocene deposits.

Till Samples from Southwestern Ontario and Eastern Michigan

Most of the samples (73) were selected from the unleached C horizon of the *upper till*. Some (26) *lower till* samples, older than the above mentioned Mitchell and Ingersoll moraines, were added for two purposes: (1) to investigate whether the general ice-flow direction was similar during deposition of both tills in each lobal area and (2) to check on the possible admixture of lower till in the upper till.

Of all the till samples investigated, 30 are from the Huron lobe area (including 3 from the Michigan side of Lake Huron) and 69 from the Erie-Ontario lobe (fig. 1).

PROCEDURE OF HEAVY MINERAL INVESTIGATIONS

Approximately 100 grams of each till sample was slightly crushed with a wooden roller and then washed through 20 and 100 mesh sieves. The -20 $+100$ mesh grade (0.15 to 0.83 mm) was retained and divided into two portions, one being used for detrital study and the remaining one laid aside as a check sample. Division of the material was made by the nine point method of sampling.

The portion for the heavy mineral study was digested in 1N hydrochloric acid to remove carbonates. Phosphates and probably some of the iron oxides also were lost in this process.

Bromoform (sp. gr. 2.87) was used for heavy mineral separation.

The basic procedure for the identification of heavy minerals was the immersion method (Dana, 1950, p. 236–239). The refractive indices of the immersion liquids ranged from 1.458 to 1.701. After the approximate limits of the refractive indices of a mineral were determined, studies of other properties such as pleochroism, extinction, elongation, and cleavage, usually completed the identification. Occasionally it was necessary to prepare a thin section of a particular mineral, using several grains.

After a mineral was identified using a petrographic microscope, its physical properties were carefully studied. In this way, once a mineral had been initially identified it was possible to recognize it again under the reflected light using a binocular microscope for counting the heavy minerals.

The following heavy minerals were found in the till samples (in alphabetical order):

actinolite (with tremolite)	2–32%
biotite	0– 2%
chalcocite	0– 1%
chalcopyrite	0– 1%
chlorite-serpentine-sericite aggregates	1–61%
chlorite-talc-sericite aggregates (in one sample only)	
garnet, light purple to colorless and orange-red	0–48%
hematite (see limonite)	
hornblende	1–68%
hypersthene	0– 6%
ilmenite (see magnetite)	
limonite (with hematite)	0–29%
magnetite and ilmenite	0–24%
marcasite (see pyrite)	
muscovite	0– 1%
pistacite	0– 9%
pyrite (with other sulphides)	0–38%
pyroxene, monoclinic (mostly diopside)	0–43%
rutile	0– 1%
sphene	0– 4%
spinel	0– 6%
tremolite (see actinolite)	
zircon	below 1%
zoisite (with clinozoisite)	1–74%

Some rock fragments were so fine grained that quantitative determination of their mineral content was not feasible. They were counted as a separate group by Moretti (1954), but excluded when calculating the percentage for this report.

Magnetite and ilmenite were counted together, as was hematite and limonite and all the sulphides, since their separation was difficult. For counting purposes a piece of light cardboard about 3 by 4 in. was ruled off with lines $\frac{1}{4}$ in. apart. The heavy minerals were spread out over this area, and the magnetic fraction (magnetite and ilmenite) was separated using a small magnet covered with a piece of light paper. All other minerals were counted under binocular microscope, using the spaced lines as traverses.

At least 300 grains were determined from each sample. If mineral fragments were very abundant, only alternate traverses were counted. When necessary, single grains were extracted for detailed determination.

Probable errors in counting and curves for their estimation are presented by Krumbein and Pettijohn (1938, p. 470–472). They show that counting of 300 to 400 grains gives a satisfactory degree of accuracy. For instance, if 300 grains were counted of which 10% were purple garnet, the range of preciseness for this mineral would be $10\% \pm 1.2\%$; if the amount of some mineral were 40%, it would be $40\% \pm 2\%$.

Descriptions of the heavy minerals studied may be found in Cook's Master's thesis (1952) and Moretti's senior thesis (1954). Therefore, they are omitted from this paper, except for the chlorite and serpentine description which is not mentioned in most published heavy mineral counts. Chlorite and serpentine occurred as rounded or irregular grains, varying in color from white to pale or medium green. Some were colorless. All exhibited pearly luster and anisotropism. Birefringence ranged from very low to high. The refractive index was moderate, about 1.580. Neither crystal form nor cleavage was apparent. A rather wide variation in the optical properties indicated a considerable latitude of composition. The grains appeared to be of an alteration product composed of chlorite, serpentine (var. antigorite) and sericite, with the first two dominant. Therefore, these are herein referred to as chlorite and serpentine whereas they were called serpentine in the first reports relative to this study.

In determining the *percentage* of heavy detrital minerals, rock fragments and Paleo-

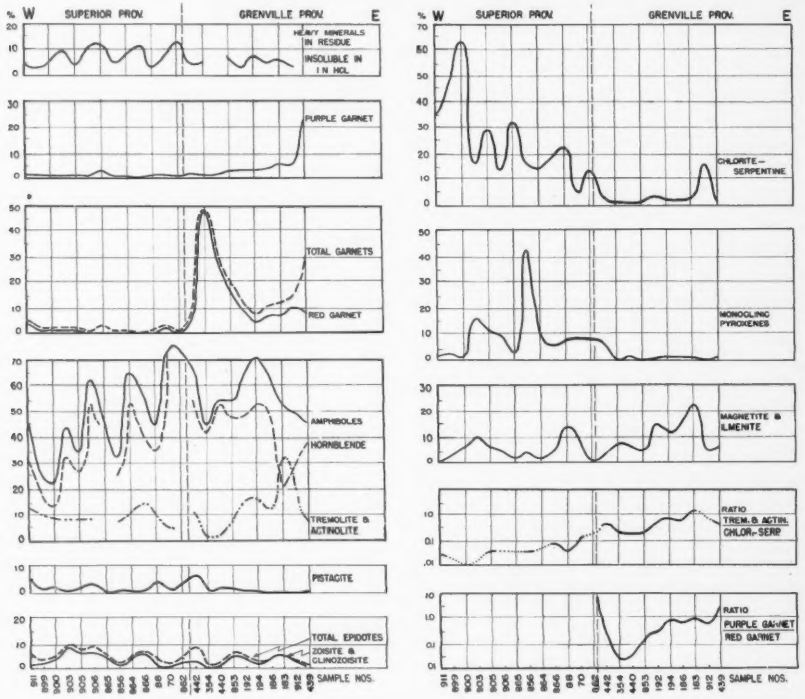

FIG. 2.—Results of heavy mineral investigations in tills along an east-west trend from Sault Ste. Marie to Montreal.

TABLE 1.—*Heavy minerals and their ratios in tills peripheral to the Canadian Shield*

	Northwest of Lake Superior (4 samples)	Between Lake Superior and Lake Nipissing (16 samples)		Grenville province and south of it (12 samples)	
	Range of percentage	Range of percentage	Modes	Range of percentage	Modes
Total percentage of heavy minerals	14–24	3–13	*5* & 12	3–8	6
Purple and colorless garnet	0–1	0–14	1	1–23	*3.5*
Red garnet	0	0–4	+	4–47	*7* & *27*
Tremolite-actinolite	4–5	8–16	9	2–35	*12*
Hornblende	1–3	12–68	30	18–55	*49*
Pistacite	+–2	0–7	*2*	0–6	1
Zoisite and clinozoisite	71–74	0–9	1 & *5*	0–5	*1* & 4
Chlorite-serpentine	2–3	2–65	4 & *15* & 33	1–16	2
Monocl. pyroxene	0	1–43	2 & *7*	0–6	<1
Hypersthene	0	0–3	+	0–13	*2*
Magnetite and ilmenite	5	0–15	.5	3–24	*8*
Ratios:					
$\frac{\text{Tremolite and actinolite}}{\text{Chlorite-serpentine}}$	1.9–2.3	0.1–1.7	0.4	0.6 –17.5	*4.5*
$\frac{\text{Purple and colorless garnet}}{\text{Red garnet}}$		.2–∞	1.2	0.02–28	0.3

zoic authigenic sulphides were excluded. Till samples from the southern boundary of the Precambrian Shield contained 2% or less detrital sulphides, while their amount increased up to 38% in the areas where Devonian shales formed bedrock. Therefore, sulphides, mostly marcasite, if in excess of 2% of the total of heavy minerals, in till samples from Southwestern Ontario were considered as local Paleozoic authigenic minerals and were excluded.

Another obviously local aggregate of minerals consisted of chlorite-talc-sericite and was found only in one sample (No. 865). It dominated there completely (68%) and distorted the percentages of other heavy minerals of that sample. When this local aggregate was excluded, the percentage of other minerals became similar to the neighboring samples.

Though similar local concentrations of a single mineral were also suspected in some other cases, in order to avoid too much a subjective interference no recalculation was applied elsewhere.

HEAVY MINERALS IN TILLS PERIPHERAL TO THE CANADIAN SHIELD

That portion of the Canadian Shield from which the till samples were taken for this study is most often divided into two provinces (Gill, 1949, p. 64):

1.—The *Grenville province*, southeast of a line trending northeast from the east end of Manitoulin island. This region is characterized particularly by metamorphosed sediments such as gneisses and crystalline limestones and dolomites.

2.—The *Superior province*, north and northwest of the above line. Simatic intrusives, volcanics, and graywackes are more common than in the Grenville province. The crystalline calcareous sediments are absent.

As the general ice flow direction was from the north and northeast during the last ice age (Glacial Map of North America, 1945), all till samples southeast of No. 862 (fig. 1) should contain heavy minerals from the Grenville province plus some of the Superior region minerals picked up by ice flows originating farther north. Those samples which were taken west of No. 442 contain minerals from the Superior province only.

The most noticeable differences between tills of both these provinces are as follows (fig. 2 and table 1):

1.—*Garnets* are more abundant in all the Grenville till samples (7–48%), when compared with tills from the Superior province (0–16%).

2.—*Amphiboles*, especially tremolite and actinolite (2–35%), *hypersthene* (0–13%) and the *magnetic fraction* (magnetite and ilmenite 3–24%) are also relatively more abundant in the Grenville tills, except for the marginal northwest and southeast samples.

3.—*Hornblende* is abundant in tills of the western half of the Grenville province (approximately 50%) and particularly northwest of it as far as the Sudbury area (up to 74%). Its percentage decreases farther west, though with considerable variations.

4.—*Chlorite and serpentine* (4–60%) and *clinopyroxenes*, mostly diopside (2–16%, in one case 43%) are more abundant in the Superior tills, with low percentages in most of the Grenville area (usually 0–2%, seldom more).

5.—*Epidotes* (*pistacite, zoisite and clinozoisite*) are also relatively more common (2–10% as a rule) in the Superior tills, with a few exceptions; they even dominate (51–76%) in some samples northwest of Lake Superior and also west of Lake Michigan (Murray, 1953, p. 147).

6.—The *percentage of heavy minerals* varies considerably (3–24%) being relatively higher in the Superior tills.

Heavy mineral content of the samples analyzed indicate that they may come principally from two Precambrian rock types: (1) from high-rank *metamorphic* rocks (garnet, tremolite and actinolite, the blue-green variety of hornblende, epidotes, micas, magnetite and some hypersthene—those without inclusions), and (2) from *basic igneous* rocks or their metamorphic derivatives (monocl. pyroxene, hypersthene with inclusions, chlorite-serpentine and epidotes).

The metamorphic minerals of the first group are particularly characteristic for tills of the Grenville province, while constituents of basic igneous rocks are more abundant in the Superior province northwest of the Grenville area.

Since the chlorite-serpentine group is quite characteristic for basic igneous rocks and for graywackes which are relatively abundant northwest of the Grenville province and tremolite and actinolite is relatively more common in the Grenville metamorphic rocks, a *ratio of tremolite and actinolite to the chlorite-serpentine* minerals may show the dominance of either of these two types. This ratio is above two, being as high as 17.5, through most of the Grenville province, but it decreases below two either just northwest of the Grenville area or in till samples from its western edge.

A separate group of Precambrian rocks is indicated by the absolute dominance of epidotes in the till samples northwest of Lake Superior (except for No. 441) and west of Lake Michigan (Murray, 1953, p. 147). They could have been derived from metamorphosed Keweenawan basic volcanics.

Each of these petrographic provinces exhibits considerable variety in its rock types. Lack of systematic investigations of heavy minerals from bedrock samples in these regions, precludes detailed discussions here regarding heavy mineral associations. If there were any very noticeable groupings or systematic changes from one area to another it was hoped these would have been detected by selecting till samples at more or less regular intervals in traverses across the ice flow direction. One such east-west section involving 13 samples extends through the southern border of the Superior region between the east end of Lake Superior (No. 911) and the west end of Lake Nipissing (No. 862). Another similar, though curved, traverse using 10 samples was selected across the southwestern portion of the Grenville province from North Bay (No. 422) through the south end of Algonquin park towards Peterborough thence east-northeast as far as Montreal (No. 439).

As changes in the abundance of both individual minerals and their genetic groups along the traverses described are shown in figure 2, they are not discussed in detail herein.

Insufficient number of till samples available from the very large Lake Superior area did not permit consideration of continuous traverses there.

It should also be mentioned that no sphene or spinel was found by Cook (1952), while Moretti (1954) noticed them in samples gathered between Cook's sample locations. As Cook may have missed them in his heavy mineral counts, changes in abundance of these two minerals are not discussed here.

HEAVY MINERALS IN TILLS FROM SOUTHWESTERN ONTARIO AND EASTERN MICHIGAN

Heavy minerals, found in tills of Southwestern Ontario and Eastern Michigan have been transported for several hundred miles from their source areas on the Canadian Shield (fig. 1). This transport by glacial ice involved crushing and abrasion. Crushing may have increased the number of fragments of brittle and hard minerals (e.g. garnet), but abrasion decreased their size and even number in the analyzed 0.15–0.83 mm grade. This decrease in size and number affects particularly the softer ones, such as the chlorite-serpentine minerals and micas.

All these quantitative changes during glacial transport must be kept in mind while interpreting results of heavy mineral counts.

Further changes may have taken place since the deposition of till, such as weathering of heavy minerals and formation of authigenic minerals, e.g. limonite. In order to eliminate these secondary changes, samples of unweathered till were taken for analyses.

Percentage of Heavy Minerals

Percentage of heavy minerals in residues, insoluble in 1N hydrochloric acid, was determined in the 0.15 to 0.83 mm grade of 49 samples of the upper till and 23 from the lower till. Since the purpose of this determination was to reveal the admixture of Paleozoic detritals in till, all sulphides in excess of 2% of the total of heavy minerals were excluded.

The Huron lobe tills contain more heavy minerals than the Erie tills (see tables 2–4 and fig. 3). The Precambrian source areas of these two lobes show similar though less distinct differences than in southwestern Ontario. The principal modes of the heavy mineral percentages in the Huron lobe area are similar in both Southwestern Ontario (4.5)[1] and the source area (5). In the Erie lobe the Precambrian source area is richer in heavy minerals (mode 6) than Southwestern Ontario (mode 1.4). The Erie tills

[1] The lowest mode (1.5) looks more prominent in figure 3, but it represents merely the Wyoming-Port Huron moraine with a larger number of samples analyzed.

TABLE 2.—*Heavy minerals and their ratios in the upper tills of Southwestern Ontario and eastern Michigan*

	Lake Huron lobe (23 samples)		Lake Erie lobe (50 samples)	
	Range of percentage	Mode	Range of percentage	Mode
Total percentage of heavy minerals in residue, insoluble in diluted HCl	0.8–11.4	1.5 & *4.5*	0.2–3.5	1.4
Purple garnet	0–8	2	3–16	*9* & *15*
Red garnet	2–15	3	5–21	*10*
Tremolite-actinolite	4–14	7	7–26	*14* & *18*
Hornblende	32–59	43	31–57	46
Pistacite	2–9	*4*	0–3	1
Zoisite and clinozoisite	*0–7*	*2*	1–5	2
Chlorite-serpentine	9–24	11 & *15*	2–12	4
Monocl. pyroxene	1–10	*3*	0–6	1
Hypersthene	0–4	2	1–6	3
Magnetite and ilmenite	3–19	7 & *12*	2–13	6
Hematite and limonite	0–20	2	0–4	1
Sulphides	0–46	<1	0–38	0
Ratios:				
$\frac{\text{Tremolite and actinolite}}{\text{Chlorite-serpentine}}$	0.2–1.2	0.3	0.9–12.5	*3.0*
$\frac{\text{Purple and colorless garnet}}{\text{Red garnet}}$	0–2.0	0.2	0.3–3.2	*0.6* & *1.0*

TABLE 3.—*Heavy minerals in tills of southwestern Ontario*

		Number of samples	Purple and colorless garnet		Red garnet		Tremolite-actinolite		Hornblende		Pistacite		Zoisite		Chlorite-serpentine		Monocl. pyroxene		Hyper-sthene		Magnetite and ilmenite		Hematite and limonite		Sulphides	
			A[1]	M[2]	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M
Huron lobe	Wyoming and Port Huron moraine	9	0–8	2	3–11	3	4–8	7	32–50	39	2–7	5	0–3	1	12–24	15	2–10	3	1–4	2	7–19	12	1–17	3	0–7	0
	Seaforth moraine	4	1–2	1	2–7	5	5–9	7.5	35–51	45	3–4	3	2	2	15–22	17	3	3	1–3	1	7–10	7	0–20	1	0–2	0
	Lucan moraine	5	1–2	2	5–8	5	7–14	12	41–59	41	3–7	3	2–7	4	11–16	13	1–6	3	0–2	1	3–7	6	0–2	3	0	0
	Mitchell moraine	5	1–8	2	4–15	11	7–10	8.5	38–54	45	3–9	5	2–4	3	9–14	11	1–4	2.5	2–4	2	4–11	6	0–11	2	0–46	0
	Lower till	7	6–16	8	3–6	5	6–12	8	37–44	37, 44	2–8	3	1–6	3	1–6	2	4–22	13	0	0	0–2	1	0–2	1		
Ont.-Erie lobe	Paris moraine	2	15–16		10		20–25		36–39		1		2		2–9		4		3–5		3–5		0–2		1	
	Tillsonburg moraine	9	8–16	10 & 15	5–13	10	12–26	20	31–46	38	0–3	1	2–3	2	2–12	6	1–6	3	2–3	2	3–9	4	0–1	1	0–12	3
	Norwich and St. Thomas moraine	11	6–13	7	6–11	8	10–25	14	35–51	46	0–1	1	2–3	3	2–7	6	0–5	1	1–6	1	2–13	6	0–2	0	0–5	0
	Westminster and Ingersoll moraine	28	3–15	7 & 9	7–21	10	7–23	15	37–57	43, 47	0–3	1	1–4	2	2–9	4	1–6	1	1–5	3	3–12	7	0–4	1	0–38	0
	Lower till	19	5–13	9	7–20	14	7–21	14	34–46	35, 45	1–4	2	1–4	2	4–23	6	1–6	4	2–3	3	3–9	6	0–1	0	1–18	1

[1] A = Amount in percent.
[2] M = Mode.

of Southwestern Ontario apparently contain more Paleozoic detritals than the Huron tills. These detritals, particularly quartz, are derived principally from the Paleozoic sandstones, more abundant along the Erie than Huron lobe.

Some differences in percentage may be observed between the lower and upper tills and the successive moraines of the upper till, particularly in the *Erie lobe*. Here the lower till contains more heavy minerals than most of the upper tills. The oldest moraines (Ingersoll and Westminster) composed of upper till, show two modes of abundance. The highest of them (2.5%) is so similar to the mode of the lower till of the same area (2.7%) that some admixture of the lower till may have occurred. The second mode (1.3) is closer to those of the following younger three moraines: 1.4 in tills from the St. Thomas and Norwich moraines, 1.6 from the Tillsonburg moraine. A marked increase is observed in the till of the youngest moraine of the area (Paris), about 3%, but the number of samples (2) is too small to permit conclusions to be made.

In the *Huron lobe* the principal difference is between the youngest Wyoming and Port Huron moraine (mode 1.5) and all the older tills (mode 4). This obvious decrease may have resulted from admixture of some local detritals from the Lake Huron basin (sandy shales?), since the heavy mineral composition is about the same in all upper tills of this lobe.

Heavy Mineral Content in the Upper Till

A summary of heavy mineral analyses of 23 samples of the upper till from the Huron lobe and 50 from the Erie lobe, is given in table 2 and figure 3.

The most conspicuous difference are in percentages of purple and red garnet, tremolite and actinolite, pistacite, and chlorite-serpentine; lesser differences are in the amount of the monoclinic pyroxene, magnetite, and ilmenite. Other minerals are at relatively equal abundance in both lobes.

The Erie tills are richer in purple and red garnet, tremolite-actinolite, and hypersthene, while the Huron tills have more chlorite-serpentine, pistacite, monoclinic pyroxene, magnetite, and ilmenite. Therefore, the ratio of tremolite-actinolite to chlorite-serpentine is considerably higher in the Erie lobe (fig. 4).

TABLE 4.—*Heavy minerals in tills of southwestern Ontario*

		Percentage of heavy minerals in residue, insoluble in diluted HCl			Ratios of some heavy minerals				
		Number of samples analyzed	Range of percentage	Mode	Number of samples analyzed	Purple garnet / Red garnet		Trem.-actinolite / Chlorite-serpentine	
						Range	Mode	Range	Mode
Huron lobe	Wyoming and Port Huron moraine	9	.8– 2.1	1.5	9	0–2.0	0.2 & 1.0	0.2– 0.7	0.3
	Seaforth moraine	3	3.2–11.4		4	0.1–0.5	0.3	0.3– 0.5	0.4
	Lucan moraine	3	3.0– 6.4		5	0.1–0.5	0.3	0.6– 1.2	0.6
	Mitchell moraine	3	3.6– 4.9		5	0.1–0.8	0.3	6.6– 1.0	0.7
	Lower till	5	3.7– 6.6	4.0	7	1.0–3.3	2.2	2.0–10.0	3.5
Ont.-Erie lobe	Paris moraine	2	2.8– 3.5		2	1.2–3.1		2.2–12.5	
	Tillsonburg moraine	9	.2– 2.8	1.6	9	0.9–3.0	1.0	2.0– 5.0	3.0
	Norwich and St. Thomas moraine	11	.8– 2.5	1.4	11	0.8–1.9	1.1	1.7– 7.3	2.7
	Westminster and Ingersoll moraine	17	1.1– 3.1	1.3 & 2.5	28	0.2–2.1	0.6	0.9– 9.0	1.3 & 3.8
	Lower till	23	1.0– 4.0	2.7	19	0.2–1.0	0.7	0.7–12.0	2.0

Some of the curves of abundance (fig. 3) have more than one mode, thus indicating their heterogeneity. This heterogeneity is due to differences in heavy mineral content between the recessional moraines, as seen in table 3.

In the Erie lobe area the percentage of purple garnet, tremolite-actinolite, and monoclinic pyroxene increases from the oldest (Ingersoll) to the youngest (Paris) moraine. There is a slight decrease in the amount of hornblende.

Heavy mineral composition of the upper till from the older, Ingersoll and Westminster moraines, is similar to that of the lower till, indicating either: (1) an admixture of the lower till with the older upper till, (2) traversing of the same Precambrian areas by the ice lobes which deposited these tills, or (3) both explanations.[2]

In the *Huron lobe area* comparing the various moraines from the oldest, the Mitchell, through the youngest, the Port Huron-Wyoming, on the basis of their heavy detritals, an increase is observed in the percentage of the mineral groups magnetite-ilmenite, chlorite-serpentine, hematite-limonite. In contrast, a decrease may be noted in the percentage of red garnet and zoisite; and barring a slight increase from the Mitchell to Lucan moraines, a decrease also may be seen in the tremolite-actinolite group.

No regular decrease or increase of any mineral has been found along the length of either the Huron or Erie moraines except for a slightly higher percentage of purple garnet (3–8) and magnetite (11–19) in tills on the Michigan side of Lake Huron (Port Huron moraine).

Heavy Mineral Content in the Lower Till

The lower till of the *Erie lobe* does not differ appreciably in mineral content from the upper tills of the same lobe. The main difference is in a relatively higher percentage of red garnet (mode 14%) and a resulting lower ratio of purple to red garnet (Knox, 1952, p. 14) than in some of the upper tills. The amount of tremolite and actinolite is lower (mode 14), particularly if compared with upper till from the Tillsonburg and Paris moraines (mode 21).

Greater differences exist between lower and upper tills from the *Huron lobe*. The lower till is richer in purple garnet (mode 8%) and clinopyroxene (mode 13%), but contains less chlorite-serpentine (mode 2%),

[2] At least the basal portion of this till contains reworked lower till (Dreimanis, 1953).

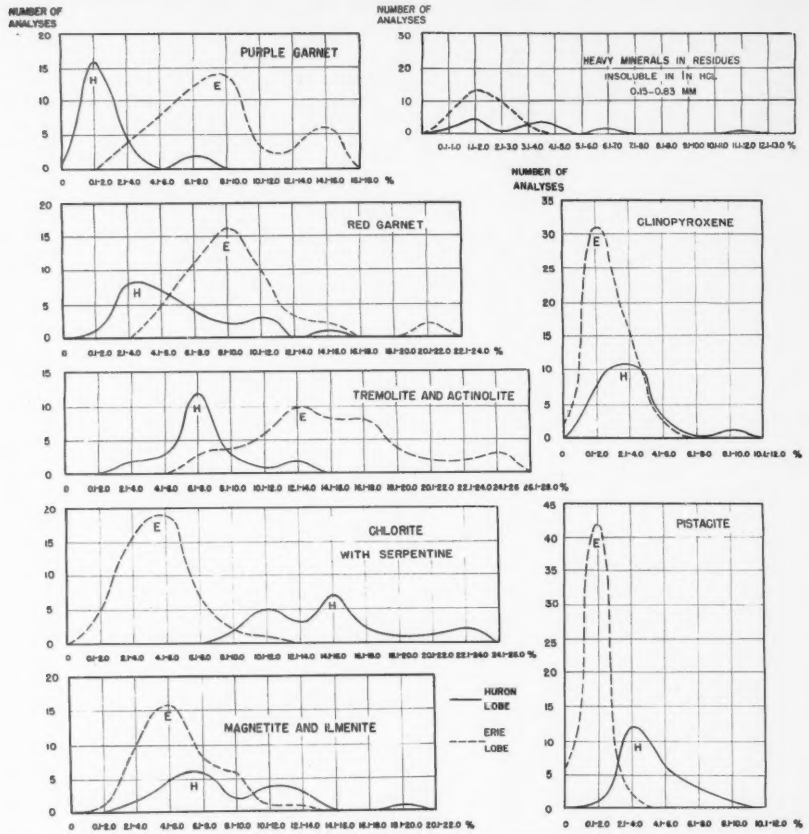

FIG. 3.—Distribution diagrams of heavy mineral content of the Huron upper till (H) and of the Erie-Ontario lobe (E) in southwestern Ontario.

magnetite-ilmenite (mode 1%) and no hypersthene. Therefore, the ratios of purple to red garnet and tremolite-actinolite to chlorite-serpentine are higher in the lower till, compared to the upper till (fig 4).

Derry's studies of Ordovician rocks of Manitoulin Island (1934, p. 86–87) may shed some light upon the composition of the local Precambrian rocks along the northern portion of Georgian Bay and North Channel. He has found hornblende and garnet as the most common heavy detritals. Insoluble remains from the Dundas Formation contain up to 40% pink to colorless garnet, possibly the variety here called purple, since it resembles pink more than the orange-red type. These garnets have probably been derived from Grenville rocks, now covered by lake waters.

Ordovician rocks of Manitoulin Island do not contain any chlorite-serpentine, probably because of its lesser resistance to abrasion. The surprisingly low percentage of chlorite-serpentine in this lower till, in association with an amount of garnet higher than in other Huron tills, could suggest a considerable admixture of those Ordovician beds from the north end of Lake Huron, which are known to contain detritals from local Grenville rocks.

ICE FLOW DIRECTIONS AS INTERPRETED FROM THE HEAVY MINERAL INVESTIGATIONS

Lake Huron Lobe

Those heavy mineral observations and considerations relative to the lower till indicate that it was deposited by an ice flow over the Sudbury-Espanola area (fig. 1) progressing over the northern portion of Georgian Bay which may be underlain by Grenville rocks. Further studies of tills from Manitoulin Island, Bruce Peninsula, and Georgian Bay are necessary for substantiation of this deduction.

Upper tills are characterized by all those heavy minerals which are found north of Lake Huron, plus some garnets, indicating again an admixture from Grenville rocks. Therefore, it may be concluded that the Huron lobe came from the region north of Lake Huron, also crossing the western end of the Grenville province or picking up Grenville minerals from basal Ordovician beds. Each of the successive recessional moraines of the upper till, beginning with

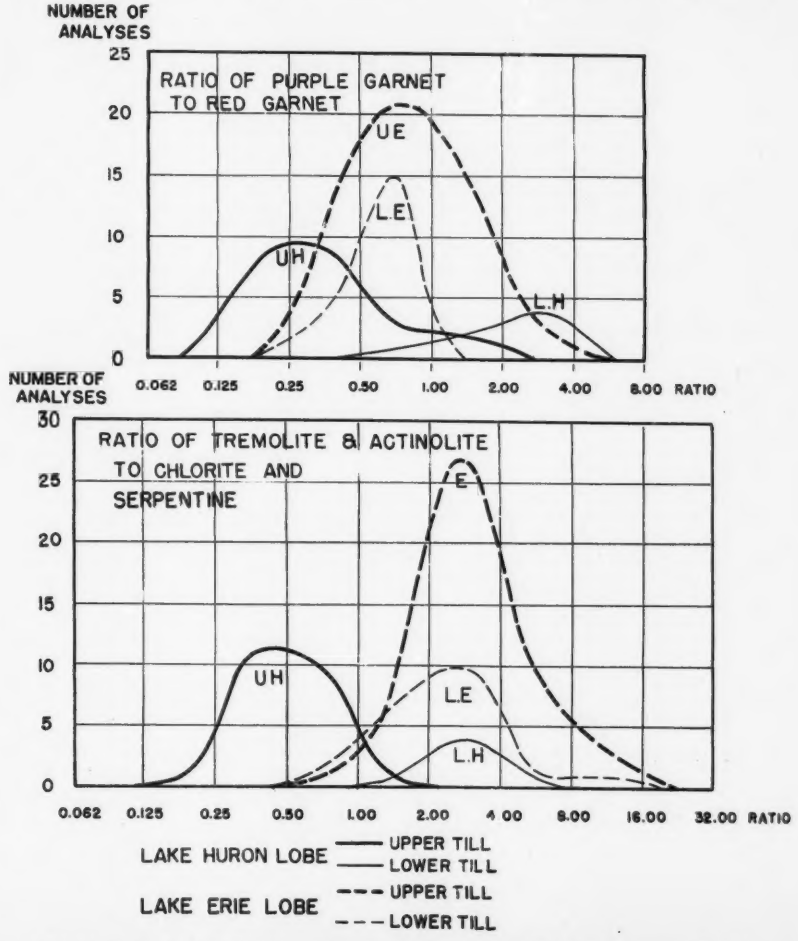

FIG. 4.—Distribution diagrams of heavy mineral ratios of tills in southwestern Ontario.

the Mitchell, show a gradual decrease in red garnet and increase in chlorite-serpentine as well as magnetite-ilmenite, except for the Port Huron-Wyoming moraine, where some samples do not follow this rule. These changes in heavy mineral content from the Mitchell to the Wyoming-Port Huron moraines suggest the following lobate movements:—the flow which deposited the Mitchell moraine, came from north-northeast, over the north end of Georgian Bay; during deposition of the following moraines, the flow shifted gradually toward the west, crossing the Sault Ste. Marie-Thessalon area; an additional flow over Georgian Bay added some of the Grenville minerals to the latest Port Huron-Wyoming moraine.

Lake Erie Lobe

Tills of the Lake Erie lobe are characterized by a greater abundance of purple garnet, red garnet, and tremolite-actinolite than in the Huron tills, with the ratio of purple to red garnet higher than 0.3 (modes 0.6 and 1.0 in the upper and 0.7 in the lower till) and the ratio of tremolite-actinolite to serpentine higher than 0.9 (mode 3.0 in the upper and 2.0 in the lower till). Such composition is also typical for the main Ontario portion of the Grenville province except for its western end, and therefore indicates an ice flow from the northeast.

Comparison of heavy mineral content between successive recessional moraines reveal a shifting of the Erie ice flow but in the opposite direction to that of the Huron lobe. First the Erie lobe came from the north-northeast depositing the lower till and the oldest end moraines of the upper till, which contain a relatively lower admixture of purple garnet, and tremolite-actinolite. Later, the axis of this Erie-Ontario ice flow shifted towards the east, as indicated by the increase of the tremolite-actinolite and the purple garnet.

Thus, both Lake Huron and Lake Erie ice lobes entered their respective lake depressions from north-northeast during deposition of the lower till and the early stages of deposition of the upper till in Southwestern Ontario. They may be considered as parallel eastern (Erie) and western (Huron) parts of a regional ice flow. These two flows gradually drifted apart, the Huron lobe assuming a more north-south, and the Ontario-Erie a northeast-southwest direction, both becoming essentially parallel with the axes of their corresponding lake depressions. The space between them did not become free of ice. It was occupied either by minor flows, feeding the Huron and Erie lobes from the sides, or these tributary flows developed into independent lobes, the Lake Simcoe-Haliburton and the Georgian Bay.

More analyses of till samples from the Precambrian area, farther to the northwest, north, and northeast may very well lead us to a greater knowledge of the ice flow directions and of the source areas of the various glacial stages and substages of Pleistocene time.

Since each successive recessional moraine has a slightly different composition of heavy minerals, correlation of them in each lobal area, on both sides of these lakes, may become possible in the future.

APPENDIX

Since this paper was submitted for publication, another till layer, older than the "lower till" has been found at Port Talbot, exposed in the Lake Erie cliff. It is even older than the Port Talbot interstadial gyttja that was deposited more than 39,000 years ago (Lamont Geological Observatory radiocarbon date No. 217A, W. Broecker, personal communications). This oldest till of the Port Talbot exposure possibly belongs to the Early Wisconsin or the Post-Sangamon, Pre-Wisconsin glaciation (Flint, 1956, p. 284–285), separated from the Main Wisconsin ("lower" and "upper" Erie tills of this paper) by a definite interstadial deposit. The heavy mineral content of this Early Wisconsin till is essentially the same as in the Erie "lower till," except for a considerably smaller total percentage of garnets (4%).

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FIGS. 1–9, JUNE, 1957

FLUVIAL GRAVEL FABRIC

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Grand Junction, Colorado

ABSTRACT

The importance of gravel fabric lies in its potential aid in determination of source area and genesis of a sedimentary deposit. Gravel fabric in fluvial sediments has received scant attention in the past because its determination is overly time consuming, and because of lack of agreement among workers on the relation between the fabric pattern and the direction of stream flow. A new method is suggested for fabric determination on unconsolidated deposits which is faster than the old procedure, and can be done in the field. Another refinement includes selecting the pebbles to be plotted on the basis of shape (disc- and rod-shape). Such selection results in a clearer fabric pattern with fewer pebble measurements.

Two streams were studied to obtain the orientation of the disc- and rod-shaped pebbles with respect to the direction of stream flow. It was found that discoid pebbles shingle, with their short axes dipping downstream at a steep angle. The long axes of rod-shaped pebbles have a limited tendency to describe a plane (as outlined by the maxima in the fabric diagrams) which dips in an upcurrent direction.

In a further attempt to reduce the time involved and still obtain the sediment transport direction, apparent dip studies were undertaken on partly consolidated ancient fluvial gravel deposits. Utilizing the results from the two stream studies, readings of the dip of the apparent long axes of pebbles were made on intersecting vertical faces of flat lying gravel, to reconstruct the upcurrent dipping plane for the sedimentation unit involved, and thereby determine the direction of sediment transport. Through comparison with other means of flow direction determination, an affirmative check on the apparent dip readings was possible.

INTRODUCTION

Fundamental to the knowledge of any sedimentary unit, is an understanding of its origin and provenance. Such problems are sometimes solved through study of the physical properties of the deposit and a comparison with presumed modern equivalents. One such property is fabric—the spacial orientation of the grains or particles in a sediment.

Any non-spherical particle has an orientation which may be described in terms of any uniquely determined axis (longest or shortest) and plotted through use of a gnomonic or stereographic projection. Careful study of the fabric in coarse clastic deposits may indicate the direction of sediment transport, and when used with other properties such as shape or trend of the sedimentary unit, the origin of the deposit.

Until recently, very few fabric studies have been made because techniques are tedious and basic interpretation of the patterns obtained is subject to some uncertainty. But, as geologists realized the importance of fabric studies in the trend determination of petroliferous Tertiary "shoestring" sands in the Gulf Coast, increasing attention has been paid to this property.

The present study of fluvial gravel fabric arose as a facet in the petrologic investigation of the Brandywine Formation (Schlee, in press)—a plateau capping of gravel and associated loam which mantles much of southern Maryland. The paucity of crossbeds in the Brandywine Formation made it necessary to investigate the fabric of the gravel to determine the sediment transport direction in different parts of the gravel sheet.

When existing methods of fabric investigation proved to be too laborious, refinements of these methods, and development of a new method were necessary. A review of the techniques and interpretation of gravel fabric is in order as a prelude to the refinements and concepts to be introduced later.

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many graduate students at Johns Hopkins for their criticisms, comments, and assistance.

TECHNIQUES

Review

Systematic investigation of gravel fabric began approximately 24 years ago, following Richter's (1932) work on pebble fabric of till in Germany. Wadell (1936) first studied pebble fabric in an esker and outwash delta and developed the method (Krumbein and Pettijohn, 1938) modified and set forth here. The method consisted of marking a horizontal and vertical line on a pebble in the outcrop, digging the pebble out of the matrix, and reorienting it in the laboratory on a two circle goniometer. Histograms were plotted of the azimuths of the long axis ("a" axis) of the pebbles and the dips of the long axes. A polar coordinate plot of the long axes was also made, and with the introduction of petrofabric methods (Knopf and Ingerson, 1938) into this country, yet another and better means of plotting data was provided, namely, the equal area polar coordinate plot (Krumbein, 1939, 1940, 1942).

The procedure outlined above has several disadvantages. It is time consuming. Approximately 1¼ hours are needed to mark 50–75 pebbles. Reorientation on the two-circle goniometer is also tedious and time consuming. Pencil marks are easily rubbed off, particularly if the pebble has a dirty surface, and therefore must be either inked or sprayed with acrylon plastic.

Modifications

In order to overcome these difficulties, two important changes were made. First, only pebbles having a rod or disc shape (Zingg, 1935) were plotted. The orientation pattern is in part dependent on the hydrodynamic conditions at the time of deposition. It was hoped that the pebbles with a distinctive shape would be oriented in a characteristic manner so that the flow direction could be determined from a fabric diagram of their long and short axes. Presumably, by eliminating the more spherical pebbles which tend to come to rest with their long axes in most any direction, a clearer fabric pattern will be obtained with fewer measurements in less time. The long axis ("a") of rod-shaped and the short axis ("c") of the disc-shaped pebbles were measured and plotted.

The second change was a new method of measurement. A cyclinder-shaped mass of plasticene (2×1½ inches) is mounted in a wooden block (5×3 inches). The pebbles are pressed into the plasticene much as teeth are pressed in red wax for denture construction. A string is stretched across the base of the outcrop, parallel to the face containing the pebbles to severe as a reference line, and its azimuth is measured (fig. 1). During the pressing process, the long edge of the block is oriented parallel to the reference string. The wooden block has spirit levels on it to insure horizontal and vertical orientation during the impressing process. When the clay is pressed against the gravel, the pebbles usually come out of the face stuck in the plasticene, or at least they make enough of an impression so that when they are dug out, they may be placed in their respective impressions in their proper orientation.

The block with the pebbles impressed in the clay is placed on a polar coordinate net which is mounted on a level 18-inch square board on which a reference line is drawn with the same direction on the net that it had in the outcrop, with pebble axis (short or long) over the center of the net. The azimuth of the axis can be recorded and the dip of the axis obtained by using a Brunton compass or inclinometer. Two experienced operators can measure approximately 35 pebbles per hour and the necessity for reorienting in the laboratory is completely eliminated thereby resulting in a saving of ½ to ⅓ the time over the old method. The data are plotted on a polar coordinate net.

The fabric diagram obtained by the impression method differs little from that obtained by the older procedures. However, by selecting the shape of the pebble plotted, a clearer picture is obtained using fewer measurements. When the long axes of 300 randomly-selected clasts from a gravel face were plotted using the Wadell method (fig. 2A), a 7% maximum was obtained, and, if one assumes that the long axes dip upcurrent, the flow direction is 55° and the upcurrent dip is 12°. As can be seen from the diagram, the maximum is low

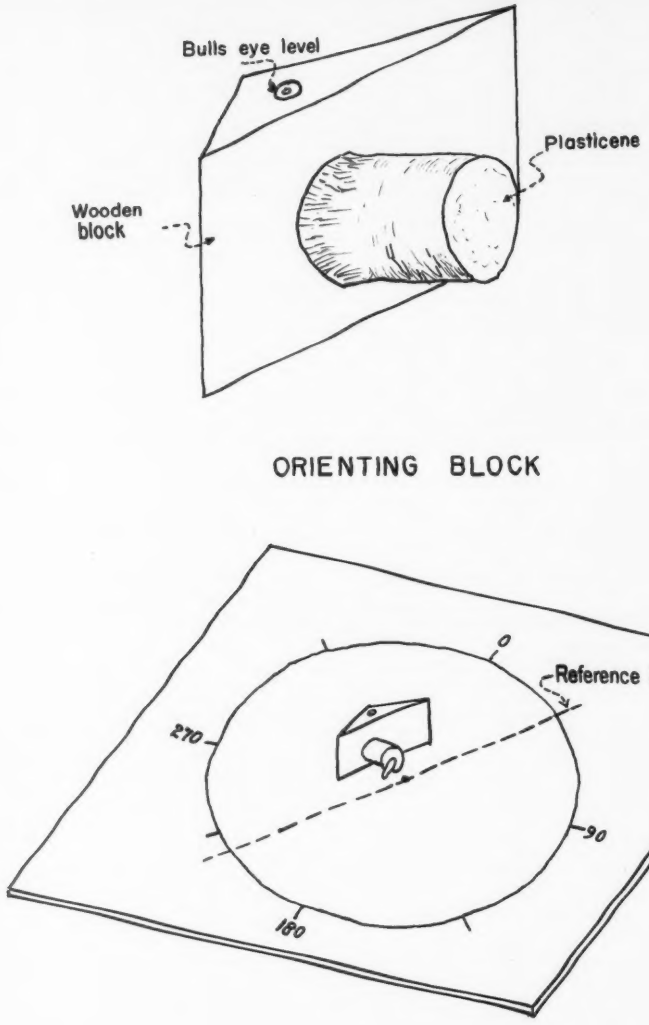

FIG. 1.—Apparatus for the impression method.

and the fabric picture is not clear because of many submaxima around the periphery of the diagram. If the same gravel be studied by selecting pebbles conforming to certain shapes such as the rod-shaped pebbles, (fig. 2B,C) it is clear that the 12% maximum obtained has an azimuth indicating a current flow direction of 70° and an upcurrent dip of 12°. If disc-shaped pebbles are chosen, the upcurrent dip of the a–b plane of the

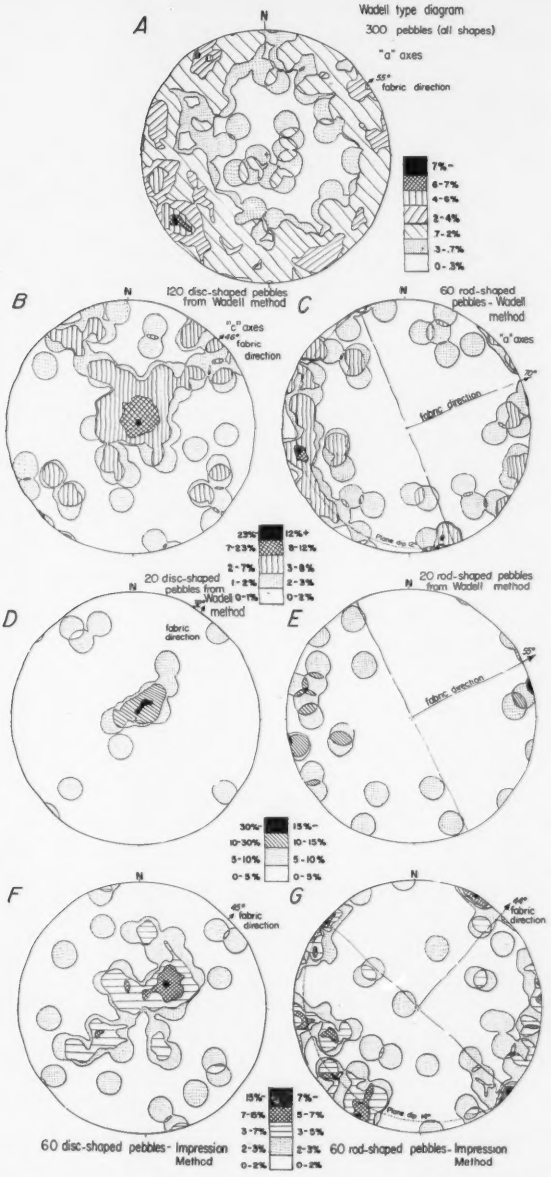

FIG. 2.—A comparison of the fabric diagrams obtained by the Wadell method and the impression method at the same outcrop.

disc (i.e. downcurrent dip of the "c" axis) can be ascertained by plotting the shortest axis (fig. 2B). These show a flow direction of 46° and a "c" axis dip of 83–84° in the downcurrent direction (or 6–7° upcurrent dip of the a–b plane). Thus, these diagrams using the Wadell method by selecting on the basis of shape, are in essential agreement with the current direction as indicated by the 300 clast diagram.

Efforts were made to determine the numerical size of the sample of disc- or rod-shaped pebble needed to obtain an intelligible diagram (using the Wadell method). Figures 2D and E show the results. A distinct fabric pattern is obtained by using only 20 discoid pebbles; a flow direction of 32° and downcurrent dip of 78° is indicated. The diagram for 20 rod-shaped pebbles is less clear; instead of a pronounced upcurrent maximum, there seems to be a scattering of the maxima and submaxima along the periphery of the diagram with minimum in the sectors perpendicular to the supposed direction of flow. If one takes the *bisectrix* of the semicircular concentration of points, a flow direction of 50–60° is indicated. In all four diagrams the flow direction does not differ by more than 23° from the direction indicated by the diagram based on 300 clasts.

In all of these diagrams, the Wadell method was used. The agreement or lack of agreement obtained using the impression method at the same locality, on the same face of gravel was next considered. A similar pattern was obtained. The "c" axis maximum (fig. 2F) indicates a flow direction of 45° and has a downcurrent dip of 68°. The fabric pattern, less definitive for rod-shaped pebbles (fig. 2G), is marked by five maxima and numerous submaxima (grid pattern). Four maxima occur at the edge and the fifth is assumed to lie in the upcurrent direction. If this maximum is taken to indicate the upcurrent direction, then the current flowed 45°. Hence, with rod-shaped pebbles one has to be content with finding prominent maxima or bisectrices of semicircular concentration of maxima to interpret the fabric pattern. As will be pointed out below, a combination of the two will give the best solution to the problem. In any case, essentially the same fabric pattern was attained using both the older and newer methods.

INTERPRETATION OF GRAVEL FABRIC

Review

Interpretation of gravel fabric patterns raises the question: just how are pebbles oriented with respect to the currents which deposit them? A review of the literature discloses a lack of agreement among various authors on the subject.

Becker (1893) noted that flat pebbles shingle upstream and rod-shaped pebbles are found lying across the channel. In substantial agreement with Becker on both points are Twenhofel (1932) and Fraser (1935). Another group of workers, which include Johnston (1922) and Krumbein (1940, 1942) state that fluvially-deposited pebbles are oriented with their long axes parallel to flow with an upstream dip. With the exception of Twenhofel and Krumbein, all base their conclusions on casual observations instead of actual measurements.

On the basis of Hunzicker's laboratory experiments, Twenhofel (1932) states, "the pebbles placed on a sand bottom in a current too weak to carry them, rotate through washing of the sand beneath them until they attain a position with their longest axis perpendicular to the current." The author has also observed similar phenomena in an experimental flume.

W. C. Krumbein (1939) studied the preferred orientation of pebbles in glacial outwash and found that the "a" axis lay approximately "in the direction of flow," although a large variation was present. Further studies by Krumbein (1940, 1942) of flood gravels of two southern California streams support this view. Pebbles of all shapes were used and the long axes were plotted on the equal area polar coordinate net. In four of the six diagrams in the San Gabriel study and all six of the diagrams in the Arroyo Seco study, the "a" axes show an upstream imbrication with their azimuths generally parallel to the valley trend; secondary maxima at angles to the valley trend were numerous.

In 1953, Murray and the author (Murray and Schlee, 1953) made a brief study of the gravel fabric in Recent terraces of the Patapsco and Patuxent rivers. The results for

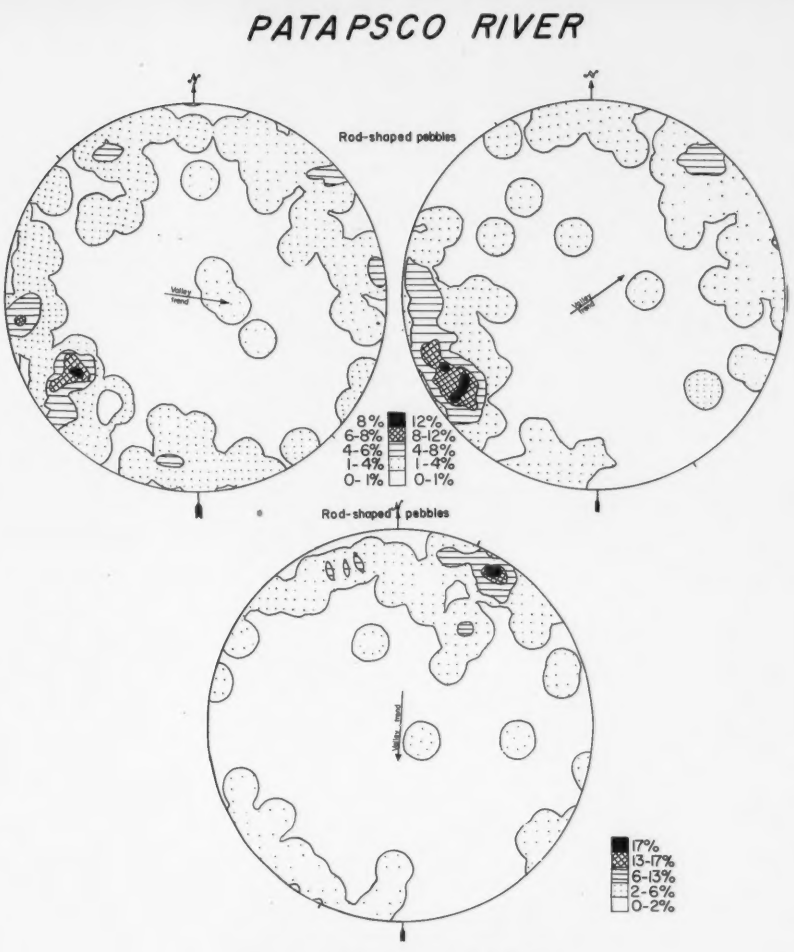

FIG. 3.—Fabric diagrams for rod-shaped pebbles in Recent terrace gravels of the Patapsco and Patuxent rivers.

rod-shape pebbles are summarized in figure 3. As can be seen, the long axes dip upstream with their azimuths approximately parallel to the valley trend. Note also the submaxima around the periphery of the diagram and the paucity of readings roughly normal to the flow direction.

In 1954, Lane and Carlson discussed the effect of pebble shape on movement of coarse sediments. They state, "It was also noticed that the elongated cobbles were usually arranged with their longest dimension to right angles to the direction of flow." Though no measurements were made, a photo was published which seems to show the elongate pebbles normal to the direc-

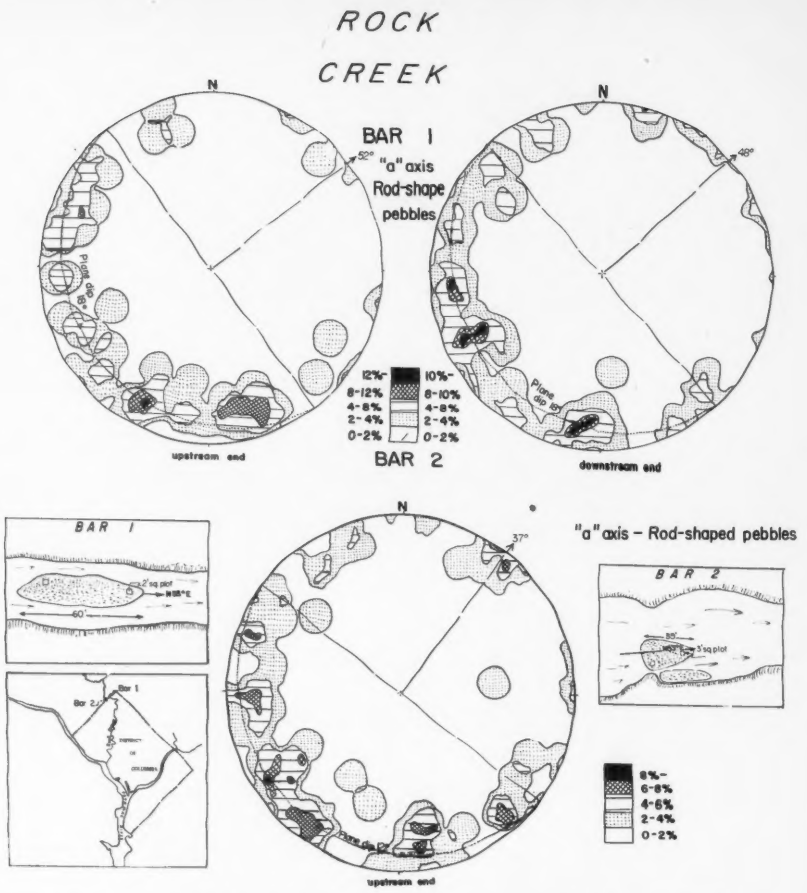

FIG. 4.—Gravel fabric of rod-shaped pebbles for two gravel bars in Rock Creek.

tion of stream flow. One cannot be sure from the picture whether this is more apparent than real in asmuch as the light is at such an angle that shadows cast by the pebbles normal to the flow direction are larger and thus make these pebbles more conspicuous than those parallel or oblique to stream flow. The authors attribute the observed orientation to rolling of the pebbles during transportation. This may be true if the bottom is smooth and hard, but perhaps difficulty in maintaining the rolling normal to current flow might be encountered on a cobble or sand bottom.

Modern Stream Studies

In view of the conflicting statements, systematic measurements on deposits of two streams were made, first, to determine by actual measurement what the pebble orientation was, and, secondly, to note the amount of variance of the readings both with respect to present local stream flow and to the overall trend of the stream itself.

Rock Creek.—Rock Creek is a southerly flowing tributary of the Potomac River which runs through the District of Columbia and Maryland (fig. 4). Data were gathered from two gravel bars at the D.C.-Maryland line near Beach Drive and Wyndale Avenue. Two plots, two-feet square were marked out, one on each end of the bar and the azimuth and dip of 50 rod-shaped pebbles were recorded for each plot. The first bar was 17 feet wide, 60 feet long, and trended 55° in a downstream direction. Most of the pebbles were in the 16–32 mm or 8–16 mm class; roughly 60% of the deposit was gravel-size material. No preferred orientation could be observed just looking at the gravel but as can be seen from figure 4, maxima and submaxima are present and are restricted to one half of the diagram which is the upstream direction. The bisectrix of the half circle gives a downcurrent direction of 52° for the sample from the upstream end of the bar and a 48° azimuth for that of the downstream end. These values closely approximate the 55° azimuth. A similar fabric was obtained for the second bar; material mainly from the 32–64 mm size grades and 16–32 mm size grades was measured. The channel direction is 53° and the current direction indicated by the bisectrix is 37°. A second diagram, not shown here, for the downstream end of the bar indicates a flow direction at time of deposition of 20°. Differences between the fabric and the channel direction result in part from a log which partly blocks the stream causing a deviation of the channel during high water stages.

In summary, rod-shape pebbles show a peripheral semicircular arrangement of the maxima, the bisectrix of which points in the downcurrent direction and point minima are present adjacent to the ends of the semicircle (figs. 2C and 4).

Moreover, there is a slight tendency—for 5 of the 9 diagrams—for maxima to lie on or

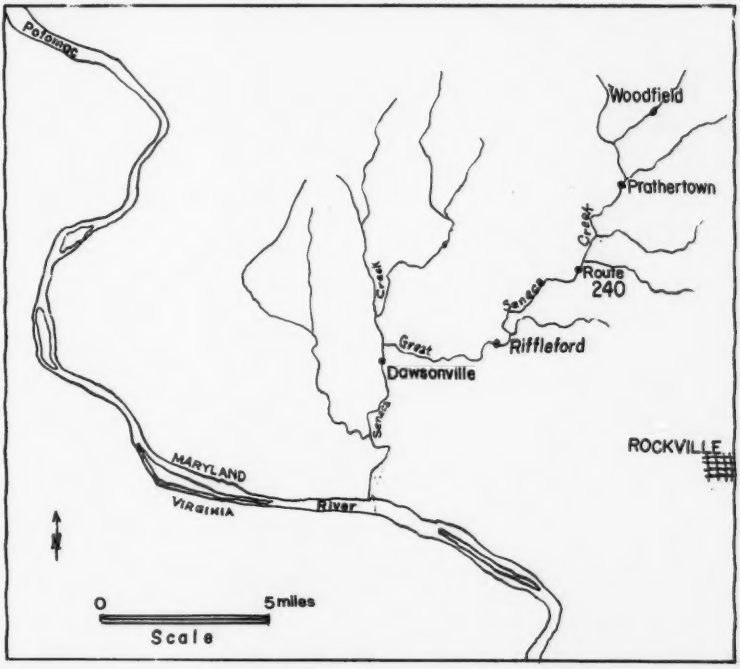

FIG. 5.—Sketch map of the localities on Great Seneca and Seneca creeks.

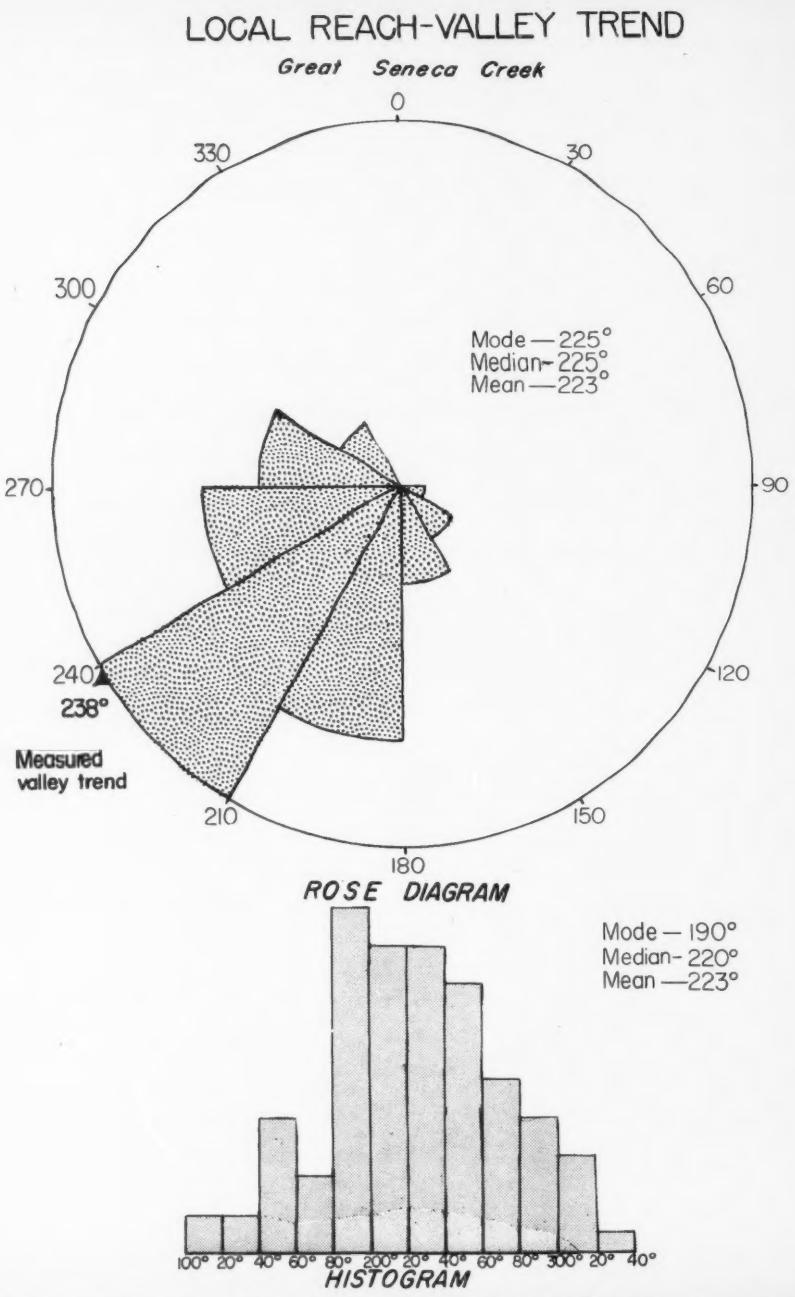

FIG. 6.—Histogram and rose diagram for the azimuths of the local reaches in Great Seneca Creek.

adjacent to a plane which dips upcurrent (dip ranges from 10–18°). The maximum dip azimuth of this hypothetical plane (figs. 2C,G, and 4) coincides in sense with the bisectrix mentioned above though in the opposite (upcurrent) direction.

Seneca Creek.—The magnitude of deviations of the mean fabric axis from the trend of the river was also studied. Errors arise from two main sources, namely, irregularities of current flow direction within a channel, and meandering or tortuosity of the river itself.

To find the magnitude of these variances, orientation of disc-shaped pebbles (16–32 mm) on gravel bars in Seneca and Great Seneca Creek were measured (fig. 5). Accessibility of the stream and the large percentage of disc-shaped phyllitic pebbles facilitated the study. First, variation between local channel direction as compared with the over-all trend of the whole stream for Great Seneca Creek was studied. When a stream channel meanders as this one does, perhaps a frequency distribution of the azimuths of its local reaches will show modes which differ appreciably from the over-all stream trend. If this is true, the mean or mode of any fabric directions obtained from a fluvial gravel such as the Brandywine, might give spurious information respecting the direction of current which deposited the gravel.

A cardboard mask, with ½-inch holes bored in it, was placed over topographic sheets. The holes are randomly spaced from ¾ to 1½ inches apart. The stream was outlined in red to facilitate its identification (Scale 1/24,000). Whenever a segment of the stream was seen through a hole, its downstream azimuth was recorded. If the segment was straight, only one reading was needed; if an L-shaped segment was encountered, two readings were taken inasmuch as two reaches were observable. More readings were necessary where zig-zag segments were observed. The results (fig. 6) plotted as a histogram (20° interval) and a rose diagram (30° interval) display a normal distribution with a mode of 190°, median, 220°, and mean, 223° in the case of the histogram, and mode, 225°, median, 225°, and mean, 223° in the case of the rose diagram. Over-all valley trend is 227° in a downstream direction. Although differences are not large (37° maximum), the shift of modes resulting from the choice of class limits is well illustrated. However, one should notice the normal distribution of the data grouping around the mean which approximately parallels the valley trend.

Errors are also apt to arise from deviation of the current within the channel. Gravel fabric, of the "c" axes of discoid pebbles, was studied on five different bars on Seneca and Great Seneca Creeks. Deviations are small (fig. 7) ranging from 8° to 20°—much smaller than channel-valley deviations. Mean direction of flow based on four readings is 238° which closely approximates the valley trend to 227°. Downstream dip of the "c" axis ranges from 76–65° and the high maxima (30–18%) further substantiate the upstream imbrication of shingle-shaped pebbles noted by previous authors. Possible causes of the channel-fabric deviation will be discussed below.

An Explanation for the Observed Fabric Patterns

A tendency for the long axis maxima and submaxima of rod-shaped pebbles to lie in a plane dipping upstream is noted. The reason for such a tendency is best comprehended in terms of discoid pebble orientation. With discs, the a–b plane (plane described by the long and intermediate axes) dips upstream or, if preferred, the short axis dips downstream. Therefore, in a disc, the long ("a") axis will lie somewhere along the a–b plane with a dip of zero (where normal to flow) up to a maximum for the plane (where parallel to stream flow).

The rod-shaped pebble is but a limiting case of the discoid pebble with a much shortened intermediate axis ("b"), however the same tendencies seem to apply. When such a pebble is normal to current flow (observed experimentally) the a–b plane of the pebble acts as an obstruction to flow and (like the disc) while the short axis may be rotated to a steep downstream dip through washing out under the upstream side of the pebble, the long axis remains horizontal. When placed parallel to flow, the c–b plane faces upstream and undermining the upstream end of the pebble results in the upstream dip of the "a" axis. The long axis in the two positions proscribes a plane which, like the disc (a–b) plane, dips up-

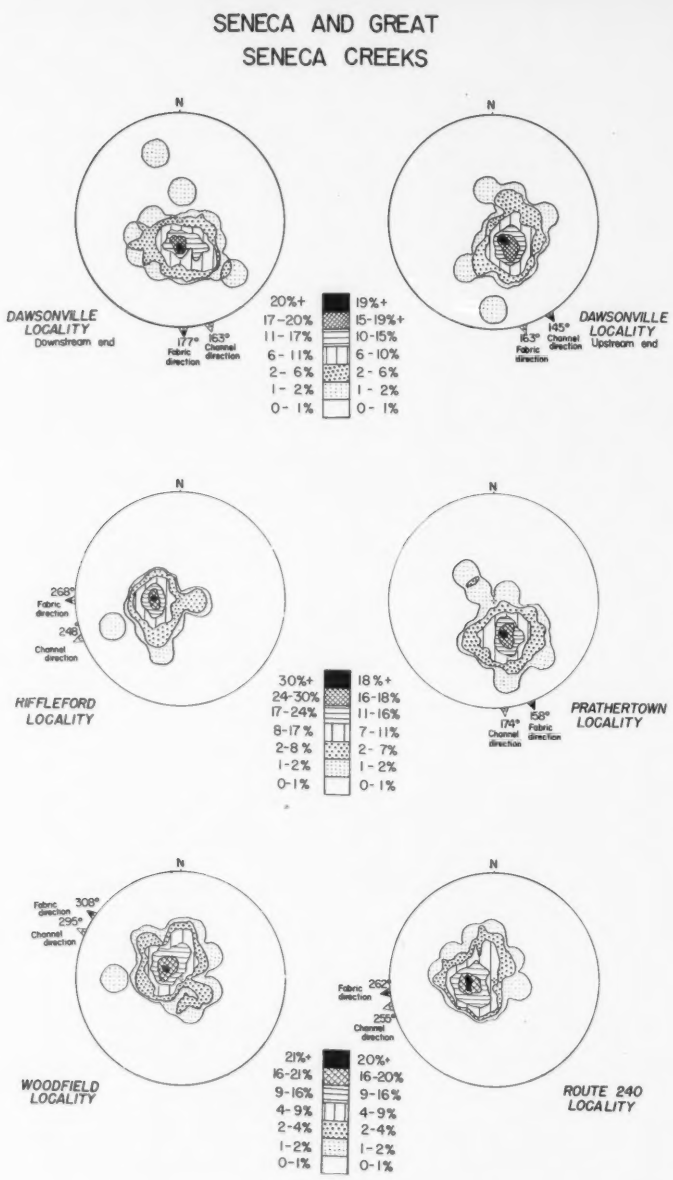

FIG. 7.—Fabric diagrams (discoid pebbles) with their indicated flow direction, in comparison with the observed azimuths of local reaches in Seneca and Great Seneca creeks.

current. Under ideal conditions, rod-shaped pebbles at intermediate angles to the direction of flow should lie on the plane because differing areas of the (b–c) plane are exposed to upstream undermining action of bottom current, which effect the dip of the "a" axis. Experimental evidence for this planar arrangement is lacking and fabric diagrams made of stream gravel are weak support because of the influence of many deterring factors to be mentioned shortly. Sarkisian and Klimova (1955) have studied azimuth orientation of rod-shaped pebbles experimentally without being concerned with the dip of the pebble axes. Rod-shaped pebbles in the center of the flume lie with their "a" axes normal to current flow whereas those adjacent of the sides of the flume are oblique to flow direction. Those to the right (looking downcurrent) are 135° to the downcurrent direction while those to the left have their long axes 135° counterclockwise to the downcurrent direction. These tendencies are not pronounced (2–4½ frequency percent over adjacent 10° sectors).

Sources of Fabric Deviation

There are many causes of the channel-fabric deviation. One notes a 32° difference between fabric direction on opposite ends of a bar in Seneca Creek (fig. 7). A possible partial explanation of these differences is suggested in figure 8. The channel current may appear to flow in straight lines, but swings or swerves from side to side to avoid gravel shoals.

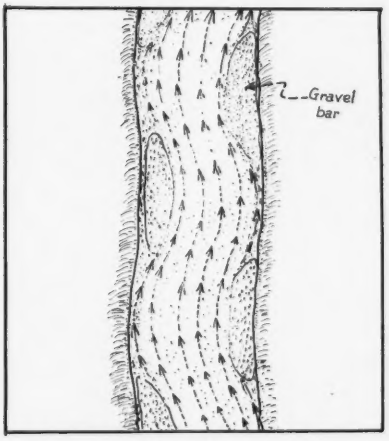

FIG. 8—Schematic diagram showing the supposed direction of channel flow around bars, to explain fabric-channel direction deviations as observed in figure 7.

Such meanderings may explain a portion of the deviation, but a large degree of scatter of points is observed within the diagrams for both rod- and disc-shaped pebbles, thereby indicating the presence of many additional factors.

The nature of the bottom has definite effect on the fabric pattern obtained. Where a sand bottom is present, excavation of the upstream end or side of the pebble is easily effected (observed in a flume) by the scouring action of impinging currents. Where sand is absent during deposition (Lane and Carlson, 1954) the force exerted by the current alone may be sufficient to hold the pebble in a preferred orientation, particularly discoid pebbles.

The effect of size on orientation has been noted by Cailleux (1945). The smallest pebbles are oriented less by current and more by the contacts with other pebbles in the stream bottom. Consequently Cailleux used only those pebbles greater than 4 cm in length. White (1952) found that he obtained the poorest results with the smaller pebbles, namely, those less than 2 inches in length. Other factors affecting orientation, according to Cailleux, are flatness (length plus breadth divided by twice the thickness) and the position of the material in the area of deposition (for marine gravels). In addition, Brinkmann (1955) states that the particle size distribution is important in determining the number of maxima obtained from the long axes of pebbles. That is, if unequal-sized materials are present, only one maximum is formed, whereas with equal-sized materials two maxima are formed. Thus, a sand base (unequal in size compared to gravel) would tend to cut down the scatter of the long axes. Brinkmann also lists shape and size as factors in the fabric pattern.

The inherent tendency to achieve some sort of stability with respect to the current and adjacent material is ever present.

The preceding discussion emphasizes the need for many more experimental studies in

which the effect of size, bottom material, particle size distribution, and shape on the fabric pattern are ascertained. Although it is not possible at present to explain the patterns obtained, this does not prevent them from being used, as will be shown in the next section.

APPARENT DIP

Introduction

The method of fabric analysis (impression method) outlined in a preceding section was used at several different stations and, for discoid fabric in particular, is probably

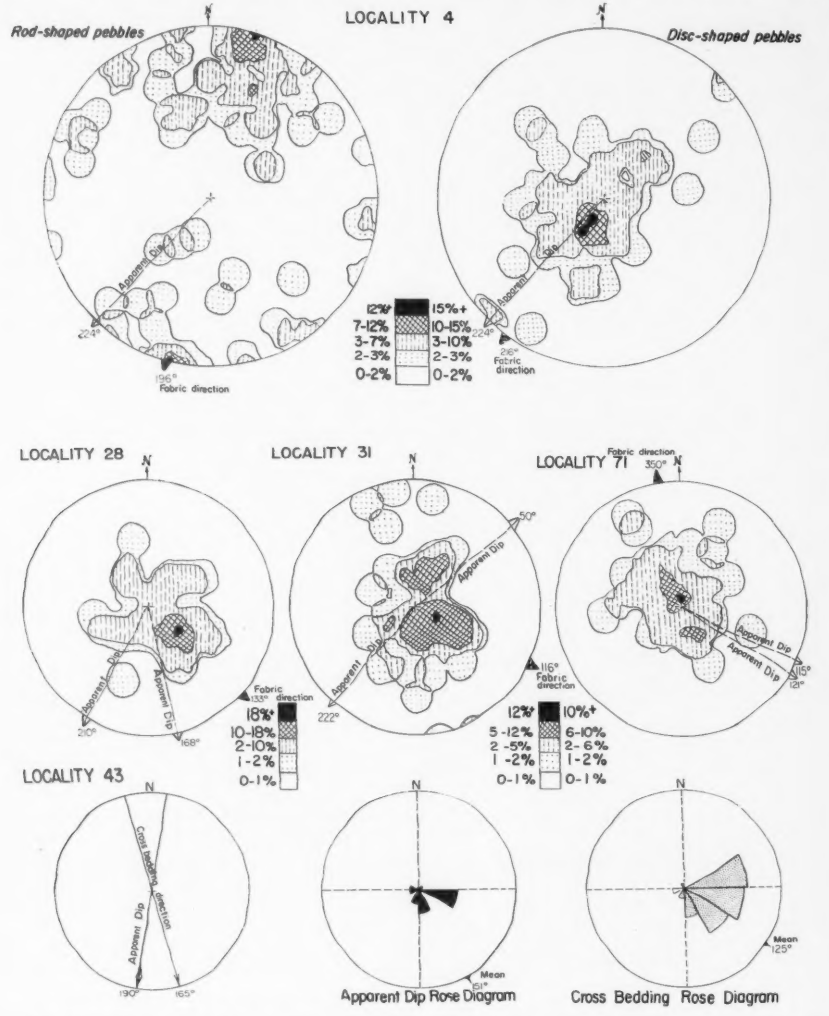

FIG. 9.—A comparison of the vector directions as obtained by the apparent dip method, to vector directions obtained in the same bed or closely associated bed, by the impression method or cross-bedding readings.

one of the most precise ways of determining the flow direction for the sedimentation unit involved. But it has two major drawbacks: it is time consuming, and, more important, it is not adaptable to consolidated deposits. Ideally, to circumvent both such difficulties, "apparent dip" studies were made in the Brandywine Formation of southern Maryland.

Normal imbrication or shingling of pebbles in exposures of terrace gravel is well known and illustrated (Pettijohn, 1949, p. 175; Schrock, 1948, p. 11). Several authors have taken advantage of this imbrication to deduce the direction of current flow from the direction in which the *apparent* long axes of the pebbles dip in the outcrop. Such studies (Johnston, 1922, White, 1952) have been made on linear fluvial deposits where the flow direction is limited to one of two azimuths. Even if the "shoestring" deposits are indurated, the principle of upstream imbrication is the same, but here we are unable to remove the pebbles to check the true orientation of their axes and perhaps select a better oriented face. All that one can do is to select a face oriented parallel to the trend of the deposit and perpendicular to the bedding planes. Because the pebbles cannot be removed, one must measure the dip of the *apparent* long axis in the outcrop face to determine the flow direction (apparent long axes are assumed to dip in an upcurrent direction).

Review

White (1952) studied apparent initial dip of pebbles in the Copper Harbor Conglomerate (Keweenawan) in northern Michigan. This conglomerate unit occurs as a tabular body roughly 2000 feet in length. Flow was assumed to be parallel to the long dimension of the lens. The apparent dip of elongate pebbles (length-breadth ratio greater than 1.5:1) was measured in vertical faces parallel to the long dimension of the lens. Pebble sizes were also recorded. White measured 388 pebbles and found a mean inclination of 8° to the southeast, the assumed upstream direction.

Cailleux also studied apparent dips and found a 2–12° inclination for pebbles in marine formations and a 15–30° inclination for pebbles in fluvial deposits. It is important to note that Cailleux observed that the inclination of pebbles depended on the orientation of the face for fluvial deposits. The median inclination varied 10–15° depending on the orientation of the face. Inasmuch as most sedimentary formations, including the Brandywine Formation, have a sheet-like configuration rather than a shoestring habit, how does one choose a face in such deposits for measuring the apparent dip of pebbles?

Method and Results

In light of Cailleux's observation and the limited tendency for the formation of an upcurrent plane described by the long axis maxima in fabric diagrams, as noted by the author, why is it not possible to measure the *apparent* inclination of pebbles on two intersecting faces of gravel, obtain the two apparent inclination means, and find by geometric construction the orientation of the upcurrent dipping plane, thereby determining the sediment transport direction? To test the validity of this approach, a fair agreement between the results of this method and the other procedures (cross-bedding and impression method) should be obtained.

The method was tested first by a comparison of the apparent dip readings for the Brandywine Formation with the cross-bedding compilation for the same deposit, and secondly, by comparing the results of the apparent dip method with those of cross-bedding or impression method at selected localities. In view of the large number of factors which can effect the fabric, the inclinations of the apparent long axis of the ten largest pebbles of a gravel face in a single sedimentation unit were measured. The mean inclination of each ten readings was taken for face A and face B and these mean inclinations were plotted on a stereonet at the azimuths of the respective faces. The plane constructed from the two means was assumed to dip upcurrent. The largest clasts were selected because it was assumed that in view of Cailleux's and White's observations on small pebbles, the orientation of the largest ones would be less affected by small bottom irregularities and controlled more by the currents.

Five localities were chosen (localities 4, 28, 31, 43, 71—numbers refer to specific

stations on the Brandywine sheet) and the results are shown in figure 9. Current azimuths at three of the five localities are in fair agreement with those obtained from cross-bedding or fabric analysis, whereas the values from the other two localities show no such agreement. The latter localities (31 and 71), however, are in a finer gravel facies of the Brandywine Formation where bedding units are not alway easily distinguished and large clasts are scarce. The lack of agreement in all cases shows the need for refinement of the technique.

The fairly close agreement in some of the localities does seem to show that the method may have some validity. If we compare the rose diagrams based on a compilation of all the apparent dip and all cross-bedding readings (fig. 9), we note that the dominant modes are adjacent in the two diagrams and the mean azimuth of the apparent dip readings is 151° (46 readings) whereas the cross-bedding mean is 126° (80 readings), a difference of 25°. Some of the difference arises from the fact that most of the apparent dip readings were taken in the western part of the gravel sheet where the larger pebbles are present. The mean should be compared, therefore, with the mean for the cross-bedding readings for the western half of the sheet. This mean is 151°—the same as that of the apparent dip measurements.

Summary

Thus, in the Brandywine Formation the apparent dip method gives fairly good agreement with cross-bedding and has proved to be a valuable device to determine sediment transport direction in those localities where cross-bedding was not present.

Great care should be exercised in using the method; it is desirable to measure the apparent long axis toward the top of the sedimentation unit, to use only the largest clasts, and to have the faces intersect at approximately 90°.

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FIGS. 1–2, JUNE, 1957

AUTHIGENIC BIOTITE IN SPHEROIDAL REDUCTION SPOTS, PIERCE CANYON REDBEDS, TEXAS AND NEW MEXICO

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ABSTRACT

Spheroidal reduction spots with dark gray bulls-eye centers have been found in the Pierce Canyon Redbeds of Texas and New Mexico. The dark gray center is a concentration of authigenic biotite disseminated between the fibrous crystals of gypsum cement.

The Pierce Canyon Redbeds of the Delaware Basin in Texas and New Mexico are a 350–450-foot sequence of brownish-red, texturally mature (Folk, 1954), thin bedded siltstone having a mean grain size of 0.04 mm with textural extremes ranging from clay size to 0.5 mm. These redbeds overlie the Rustler Evaporites (upper Permian) and are overlain by the Santa Rosa Sandstone (upper Triassic). Miller (1955) considers them to be Permian. The mineral composition of the Pierce Canyon Redbeds is relatively uniform and consists of 50 to 60% subangular plutonic igneous quartz; 15 to 30% brilliantly fresh orthoclase and sanidine; less than 5% fresh microcline; less than 1% fresh plagioclase; less than 1% detrital chert; 1–2% muscovite, biotite, chlorite, and metamorphic rock fragments; 1–3% magnetite-ilmenite, tourmaline, zircon, leucoxene, apatite, and garnet; 5 to 10% illite and hematite; and 2 to 5% calcite and gypsum cement.

Gray-green reduction spots and zones in the Pierce Canyon Redbeds range from microscopic specks to entire beds an inch or two thick. The gray-green color in similar rocks has been attributed by Keller (1953, p. 5) to illite. Some of these reduction zones are the result of leaching after consolidation and jointing; other smaller, nearly spherical reduction spots are much older and formed prior to jointing, because many of them are cut and separated by gypsum-filled fractures and joints.

A few spheroidal reduction spots contain a dark gray central nucleus or core as illustrated in figure 1. The largest reduction spot found has a diameter of 25 mm, but diameters of 3 to 10 mm are most common. There are at least two mineralogic differences between the gray-green reduced part of the rock and the surrounding more typical brownish-red matrix: (1) within the reduced zone magnetite and ilmenite are absent, or present only in minor amounts because they have been dissolved (Miller and Folk, 1955, p. 341), and (2) there are characteristically a few orthoclase grains within each reduced zone that have abnormally thick overgrowths. Only a few of the orthoclase grains in this formation have overgrowths and these are very thin, barely covering the edges and corners of the grain. Within the reduction spots the thickness of the orthoclase overgrowths is about half the width of the detrital grains.

The following description is that of a typical spheroidal reduction spot as illustrated in figure 1:

1.—The center of the reduction spot shows as a light colored circle inside the dark circle. It consists of typical Pierce Canyon detritus—quartz, feldspar, mica and heavy minerals, cemented tightly by fibrous gypsum and sparry calcite cement. Magnetite-ilmenite and hematite are lacking and there is no biotite in this zone.

2.—Surrounding the central light-colored zone (1) is a dark gray circle (sphere) consisting of the same detrital minerals and cement. The dark color is due to a concentration of medium-brown, weakly pleochroic flakes and shreds of biotite, 0.05 mm or less in length disseminated between the fibrous gypsum crystals. The biotite occurs as shredded flaky masses (fig. 2) not as well-developed individual flakes. These shreddy masses are concentrated in a nearly perfect sphere around zone 1, the individual

flakes and shreds being parallel to the long dimension of the crystals of gypsum cement. Most of the feldspar grains within this zone have pitted or irregularly corroded surfaces. They typically show more internal alteration along the cleavage planes than does the feldspar in the red part of the rock. In a few places, minute flakes of biotite are disseminated along these corroded surfaces and along the altered cleavage planes within the feldspar grain. The detrital biotite flakes in zone 2 have a fresh appearance with unusually smooth surfaces and edges (fig. 2). The detrital biotite, which occurs in small amounts throughout the Pierce Canyon Redbeds, is distinctly larger, occurs as well-developed sub-hexagonal flakes, is darker brown and more intensely pleochroic than the authigenic biotite.

3.—The next larger zone is slightly darker than the outermost sphere (4) and is not apparent in the photograph. Zone 3 contains the same detrital minerals and cement as zones 1 and 2. The slightly darker color is caused by sparsely disseminated authigenic biotite between the gypsum crystals.

4.—The outermost sphere is light gray with a pale-green hue. It contains the same detrital mineral assemblage and cement as the other zones. The outer boundary is an evenly-rounded contact separating an abrupt change from light gray to brownish red which distinguishes this type of reduction spot from the more common leached reduction spots that have irregular shapes and gradational color contacts.

The presence of biotite in these reduction spots was first identified with the petrographic microscope by R. L. Folk, Department of Geology, The University of Texas. E. J. Weiss, Department of Ceramic Engineering, The University of Texas, confirmed Folk's identification of the mineral biotite by X-ray. The biotite is believed to be authigenic because of its concentration and spheroidal distribution, its parallel orientation between fibrous gypsum crystals, its dissemination in altered feldspars, its vertical distribution across bedding planes that pass through the central spheres 1 and 2, and its smaller size, different shape, and different color as compared to the detrital biotite.

The possibility that the biotite mass might be an accretionary aggregate of detrital biotite, dropped like a mud-ball into the silt, is discounted because of the lack of concentric orientation of the biotite flakes themselves and the fact that bedding planes and parallel-oriented quartz silt grains pass from the surrounding rock right through the biotite mass without deflection.

DISCUSSION

The origin of the red color in redbeds has been aptly discussed by Van Houten (1948),

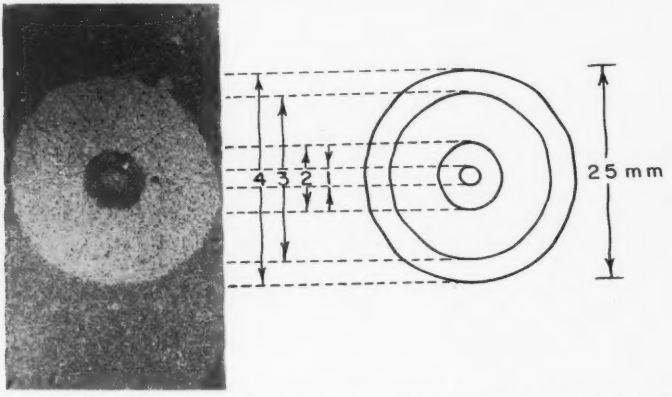

FIG. 1.—Spheroidal, gray-green reduction spot with dark gray center of authigenic biotite, Pierce Canyon Redbeds, Texas and New Mexico. Concentric circles show extent of color and mineral variation within the otherwise brownish-red siltstone.

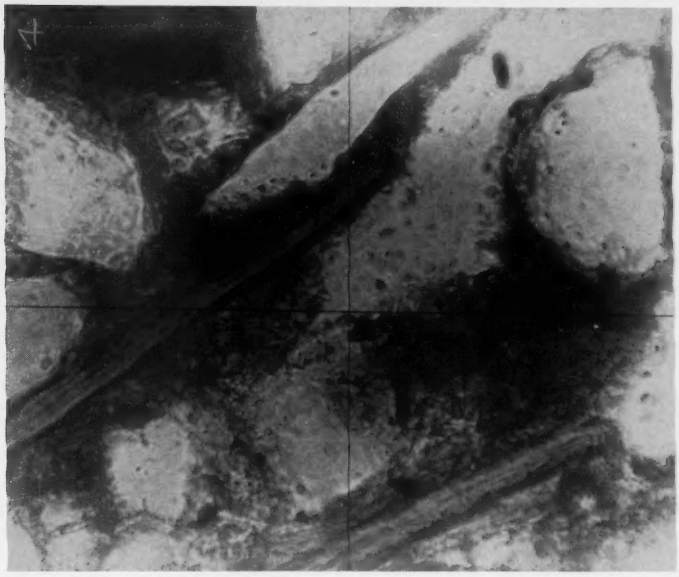

FIG. 2.—Photomicrograph of thin-section showing the shredded flaky dark mass of authigenic biotite between the silt-size quartz grains and the larger elongate flakes of detrital biotite. × 400.

Krynine (1937, 1949, 1950), James (1954) and a host of others mentioned in the reference lists of these recent articles. Krumbein and Garrels (1952), ZoBell (1946) and others have studied the stability limits of iron oxides and provided additional references on the chemistry of oxidation-reduction in recent sediments. None of these investigations provide information that can be readily applied to the removal of hematite, magnetite-ilmenite, and the formation of authigenic biotite and authigenic feldspar although Curry and Curry (1954) reported authigenic biotite from the muddy sandstone of Wyoming.

Any explanation concerning the origin of this authigenic biotite must also explain: (1) the spheroidal shape of the reduction spot; (2) the abrupt color change from pale gray-green to red along the evenly-rounded border of the reduction spot; (3) the alteration of the feldspar grains inside the reduction spot; (4) the abnormally large overgrowths on a few feldspar grains; and (5) the absence of hematite, magnetite, and ilmenite.

It is assumed that the chemical changes that have taken place within the reduction spots did so in a fluid medium. It is also assumed that the fluids which reduced and then dissolved the iron oxides also corroded and altered the feldspar grains; hence, iron, potassium, aluminum, and silica ions were probably present as the result of solution. Finally, these ingredients are believed to have combined and precipitated as authigenic biotite flakes in the accessible void space and as authigenic feldspar overgrowths on selective grains. The nearly perfect spherical shape of the reduction spots and the concentric spheres of biotite suggests that the alteration in color from red to gray-green happened after consolidation of the sediment and that the authigenic biotite formed contemporaneously with the reduction and solution of the iron oxides. The position of the disseminated biotite flakes between the fibrous gypsum crystals and along the altered cleavage planes of the feldspar suggests that these were the channels through which the fluid moved during the alteration process.

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FIGS. 1–5, JUNE, 1957

DOLOMITE GROWTH IN CORALLINE ALGAE[1]

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ABSTRACT

Thin-section study of dolomitized limestone of Eocene age from the subsurface of Eniwetok reveals the localization of dolomite crystals within segments of articulate coralline algae. Corals and large Foraminifera are little affected. The writer suggests, in view of recent work by others on the crystal chemistry and occurrence of high-magnesian calcite, that the dolomitized algae are the end product of the crystallographic ordering of the Ca-Mg solid solution that made up the original high-magnesian algal calcite. This ordering is thought to take place on scattered dolomite nuclei inherent in the original algal precipitate, these nuclei being the result of local concentrations of Mg ions within the algal calcite.

INTRODUCTION

During the deep drilling operation on Eniwetok Atoll, described by Ladd, et al. (1953), a dolomitized core was recovered from a depth of 4078 to 4100 feet. The age of the core was determined as Eocene by Cole (in press) on the basis of larger Foraminifera. The core is made up of cream-colored, dense, vuggy, coraliferous, conglomeratic, dolomitized limestone containing a high percentage of calcareous algae and Foraminifera as fossil elements. This paper deals only with the dolomite from this single core; the subsurface geology of Eniwetok is the subject of a long-term investigation.

PETROGRAPHY OF THE DOLOMITE

Dolomite in much of the core is restricted to rod-shaped segments of articulate coralline algae. These algal rods, where not too greatly recrystallized, are identifiable as *Corallina* as figured by Johnson (1954, pl. 12). The rods appear in thin section as dark circles, ellipses, or rectangles according to the orientation of their long axes with respect to the plane of the thin section (figs. 1, 2). Figure 1 shows a typical dolomitized algal rod, cut parallel to its long axis, 0.3 mm wide by 1.7 mm long. The original algal rod is almost completely replaced by clear dolomite across its width and is recognizable only by a small amount of algal material at each end. The dolomite crystals are definitely restricted to the algae and their growth seems to be controlled by the shape of the rod. The area near the axis of the rod is occupied by a fine-grained mosaic of anhedral dolomite that grades outward into coarser, more euhedral crystals. Under crossed nicols the rhombic habit of some of these crystals shows up more clearly due to separate extinction. In a section cut perpendicular to the long rod axis, the dolomite shows up as a rosette of subhedral crystals radiating from a center of fine-grained anhedra (fig. 3). Many algal rods contain separate euhedral dolomite rhombs that apparently are not so closely controlled by the shape of the algal fragment. Figure 3 shows, in addition to the transverse section mentioned above, one such rod cut parallel to its axis. In this longitudinal section three dolomite rhombs are well developed. The rhomb on the left has a cloudy, dark center typical of many of these euhedra. The crystal on the extreme right displays two faces, on opposite sides, that grade into the original algae; this lack of sharp crystal boundaries is common.

In any given thin section some rods may be completely dolomitized whereas a few millimeters away a similar rod may bear no trace of rhombs. In general, however, most of the rods are approximately half replaced by dolomite. Some thin sections show circular, ellipsoidal, and rectangular areas of dolomite that have apparently obliterated the original algae and spread into the matrix. Although not all of the algal rods in some thin sections are dolomitized, almost all of the dolomite is restricted to the rods. Some dolomite is scattered through the matrix but this is thought to have originated in small pieces of algae that are now completely re-

[1] Publication authorized by the Director, U. S. Geological Survey.

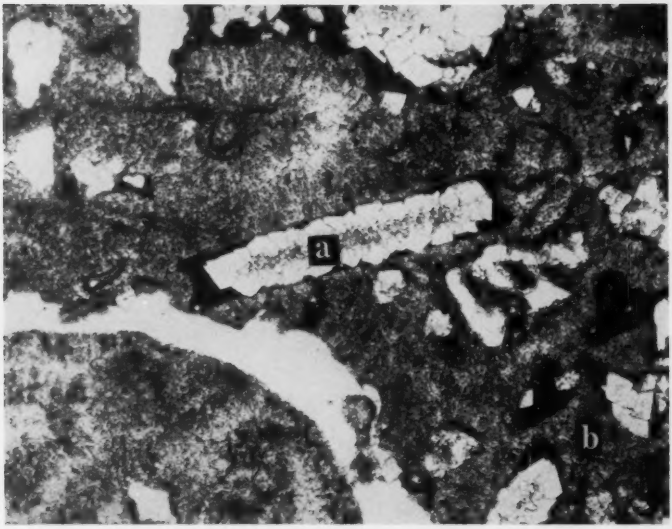

FIG. 1.—Photomicrograph of longitudinal section (a) of a segment of dolomitized articulate coralline algae, possibly *Corallina*. The black patches around (b) in the lower right hand corner are also fragments of dolomitized algae. ×30.

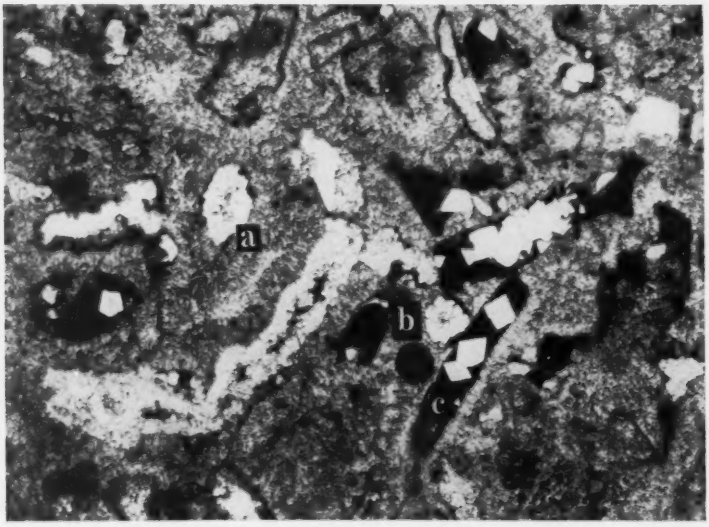

FIG. 2.—Photomicrograph of several dolomitized, rod-shaped algal segments. At (a) is a section cut at an angle to the rod axis which shows as an elliptical mass of crystals; the algal origin is revealed only by the narrow, discontinuous black rim. Just to the right of (b) is a transverse section and at (c) a longitudinal section. ×30.

FIG. 3.—Close-up view of area enclosing (b) and (c) of figure 2. ×180.

crystallized. In some slides secondary solution has removed much of the undolomitized algae and left only clusters of dolomite rhombs associated with voids.

Figure 4 shows the typical state of preservation of coral in this core. The coral structure itself is not affected by the dolomitization that is restricted to the interseptal filling. This filling seems to be in part composed of fine detritus, some of which may be algae as suggested by the numerous black flecks in the now crystalline "paste" fill. It is thought that this finely divided algal material serves as centers for dolomitization.

Also of interest is the behavior of the larger Foraminifera in this material. These fossils resist dolomitization strongly and remain unaffected when the remainder of the rock has been completely recrystallized to a mosaic of dolomite. Even at this late stage only a few rhombs are seen in the test walls of the large Foraminifera.

FORMATION OF DOLOMITE

The high magnesium content of calcitic algae has long been known. Recent work by Chave (1954a) shows that these algae, among which he lists *Corallina*, contain from 7 to almost 30 percent $MgCO_3$ by weight. He also showed that the $MgCO_3$ content is directly proportional to the temperature of the water in which the algae grew. Goldsmith Graf, and Joensuu (1955) found Mg in some algal material in concentrations greater than those indicated by X-ray study. From this they conclude that:

> "... finely divided or adsorbed Mg exists in some other form than in the calcite structure in at least some of the algal materials."

The differentiation of high-magnesian calcite from dolomite, in a crystal-structure sense, is important in any discussion of dolomitization of algae. Chave (1952) believed that X-ray and chemical studies demonstrated a partial solid solution between the minerals calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$. However, Goldsmith, Graf and Joensuu (1955) state that the use of the expression "solid solution between calcite and dolomite" by Chave (1952) is permissible compositionally but fails structurally to take into account the

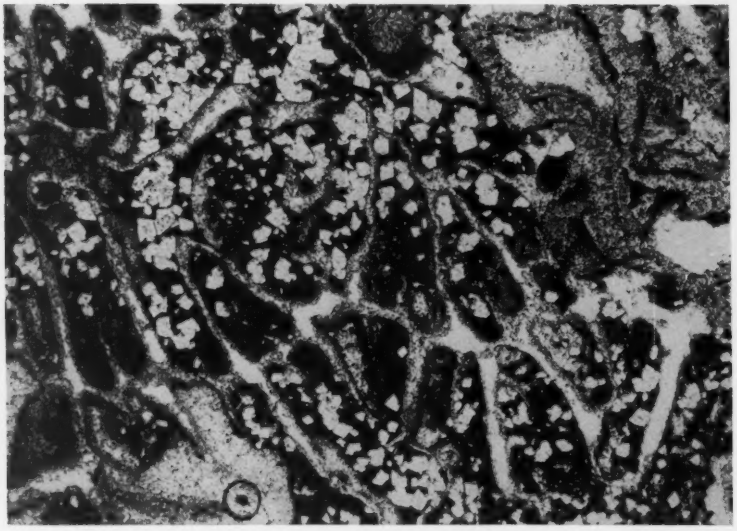

FIG. 4.—Photomicrograph of coral showing dolomite rhombs restricted to dark, interseptal "paste" and supposed algal detritus. The coral structure is not dolomitized. ×30.

ordered nature of dolomite with respect to the Ca and Mg ion positions. The dolomite structure involves the ordered substitution of Mg ions into approximately 50 percent of the Ca ion positions in the lattice. The Mg and Ca ions occupy separate and alternating cation planes. Thus the random addition of more Mg ions from sea water to a magnesian calcite would not result in a true dolomite phase inasmuch as an ordering process must also take place.

In the light of the above information and the well-crystallized dolomite in the Eniwetok material, the writer was led to the following line of reasoning in an attempt to explain the dolomite crystals in the *Corallina:*

1. There is no reason to assume that the Mg ions in the algal solid solution are distributed in equal concentration throughout. There may be regions within the algal fragment in which the Mg-ion concentration is in excess of the "average" for the fragment that is shown by a chemical analysis. Chave (1954a) showed that a considerable variation exists within a single algal colony, possibly due to seasonal temperature variation. Other factors may influence the metabolism of the algae and induce short term high uptake of magnesium. Some statistical fluctuation of cation distribution within a solid solution would also be expectable and thus there would be a few centers within high Mg regions where the Ca and Mg ions are in the ordered condition which defines true dolomite structure.

2. Thus the alga, as it grows, may contain scattered dolomite nuclei, perhaps only a few unit cells in size. These nuclei, at this stage, would be too small to be resolved by X-rays.

3. Through time the dolomite nuclei, evidently more stable than the surrounding Ca-Mg solid solution under existing conditions, enlarge by diffusion of the Mg ions in the structure, by the ordering of Mg ions originally only adsorbed, and by the addition of Mg ions from the sea water.

Chave (1954b) considered that the magnesium in solid solution with calcite is unstable and that eventually a new form should develop. As one of three possible processes by which equilibrium may be reached he believed that the magnesian calcite could reorganize crystallographically into two stable phases: low-magnesian cal-

cite and dolomite. He considered this type of dolomitization of little importance. In giving examples of fossil evidence of crystallographic reorganization Chave (1954b) fails to make clear whether the dolomite phase is inferred from the $MgCO_3$ content or is present in the true dolomite structural sense.

D. L. Graf and J. R. Goldsmith used single-crystal and powder diffraction techniques to determine the structure and composition of the dolomite from Eniwetok submitted by the writer (personal communication). They found that the dolomite deviated some 5 mol percent from the theoretically ideal 1:1 Ca:Mg ratio in the direction of excess $CaCO_3$. The partial filling of some Mg ion planes by Ca ions is indicated. Goldsmith also reported (personal communication) that the dolomite crystals contain very small calcite particles in random orientation.

The writer believes that the addition of large amounts of Mg ions from the surrounding sea water need not be a requirement for dolomitization of coralline algae because (1) perhaps as much as 20 to 25 percent of the cation positions (not considering high values found by Chave, 1954a) in growing algae may be initially filled with Mg ions; (2) ordered dolomite crystals can form with only 45 percent of the cation positions filled by Mg ions; and (3) calcite particles probably account for several percent of the crystals volume.

Graf and Goldsmith (1956) point out the difficulty of crystallizing dolomite at low temperature and attribute this difficulty to the decrease of the probability, at low temperatures or during rapid crystallization, that ideal cation sorting into ordered positions can take place. They also point out that:

> "Ultimately, an understanding of dolomite formation at earth-surface temperatures must include the mechanisms by which ordered dolomite nuclei are formed. . . . "

The writer suggests that: (1) the effect of time—the algae in the Eniwetok core are from 40 to 60 million years old—may be greater than generally assumed in low temperature environments and (2) the nuclei of dolomite may be inherent in the original algal precipitate as the result of environmental conditions, such as occasional water temperatures of over 30° C, under which crystallographically local high

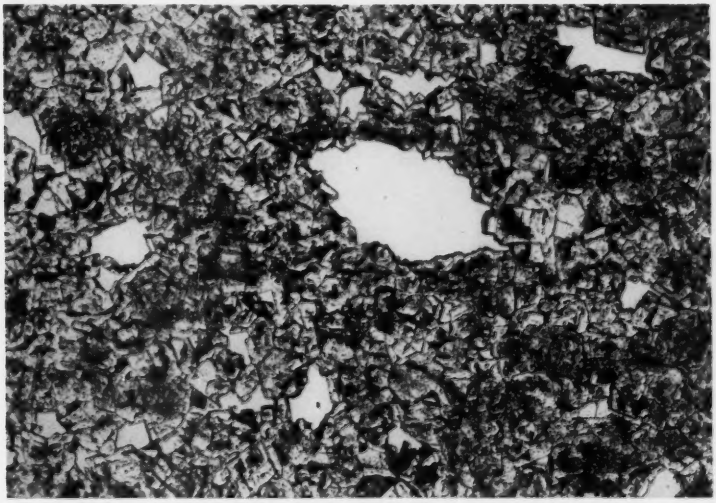

FIG. 5.—Photomicrograph of completely dolomitized portion of rock. All fossil traces and original textures have been obliterated by the development of a closely-packed mosaic of dolomite crystals. ×30.

Mg-ion concentrations may build up. The dolomitized coralline algae figured and described in this paper demonstrate the extent to which dolomite growth in high-magnesian calcite can proceed.

Petrographic evidence indicates that the final stage of dolomitization is the complete obliteration of all organic remains and original textures (fig. 5). The amount of magnesium needed for this complete alteration precludes a solely algal source for all the dolomite. In the case of massive dolomite the sea water must act as the supplier of magnesium. Thus the high-magnesian algal calcite may merely serve as a trigger, initiating dolomite growth.

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CLASSIFICATION OF LIMESTONES AND DOLOMITES ON BASIS OF Ca/Mg RATIO

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ABSTRACT

Because of shortcomings of the existing classifications of dolomites and limestones, a new classification on the basis of Ca/Mg ratios is proposed, with some divisions dictated by the ratios which are determined by the mode of formation.

INTRODUCTION

The usefulness of Ca/Mg ratio for classification of limestones and dolomites became evident during the progress of the research, which showed the importance of Ca/Mg ratio in limestone studies (Chilingar, 1956). The Ca/Mg ratio was found to be a useful geologic tool: (1) as a relative geologic thermometer, (2) for identification of limestones, (3) in porosity studies, and (4) for correlation purposes.

In addition to being a useful tool for postulating the origin of limestones, the Ca/Mg ratio is also of great importance to industrial users.

The $CaCO_3$ and $MgCO_3$ can be present in seven different forms: (1) aragonite, (2) calcite, (3) magnesite, (4) dolomite, (5) solid solution between calcite and dolomite (in skeletons of organisms—Chave, 1954), (6) nesquehonite, and (7) hydromagnesite. Although quite rare, the presence of the latter two forms has been shown by Frolova (1955) in the carbonate-sulphate rocks of Kuybyshev area, USSR.

Aragonite is an unstable form and reverts to calcite with time. Therefore, it is rarely found in Paleozoic limestones.

A new classification of limestones and dolomites on the basis of Ca/Mg ratio is shown in table 1. The limits of Ca/Mg ratio proposed in this classification are not entirely arbitrary and the basis for separation is explained for each group.

1. *Magnesian dolomites* (*Ca/Mg = 1–1.5*). A pure dolomite has a ratio of *1.648*:1; however, some dolomites contain an excess of magnesium. These dolomites possibly are the result of the precipitation (chemical) of an excess of $MgCO_3$, which can occur at elevated temperatures. Some hydrothermal dolomites can be placed in this group.

2. *Calcareous dolomites* (*Ca/Mg = 1.7–3.5*). The upper limit of calcareous dolomites was chosen because the Ca/Mg ratio of 3.44:1 is the lowest ratio known in the skeletal structures of organisms (Ca/Mg of *Goniolithon*, a genus of calcareous algae = 3.44).

Many dolomites fall in this group. They could result from an excess precipitation of $CaCO_3$ over dolomite, or incomplete dolomitization. Secondary epigenetic dolomites of this group, which resulted from the circulation of ground water solutions, can be easily identified by wide variation of Ca/Mg ratio over short distances (Chilingar, 1956, p. 12).

3. *Highly dolomitic limestones* (*Ca/Mg = 3.5–16*). Many limestones, which have a Ca/Mg ratio of 3.5 to 16, are called dolomites. Although the skeletal structures of

TABLE 1.—*Classification of limestones and dolomites on basis of* Ca/Mg *ratio*

Name	Range in Ca/Mg ratio
Magnesian dolomite	1–1.5
Dolomite	1.5–1.7
Slightly calcareous dolomite	1.7–2
Calcareous dolomite	2–3.5
Highly dolomitic limestone	3.5–16
Dolomitic limestone	16–60
Slightly dolomitic (or magnesian) limestone	60–105
Calcitic limestone	>105

Note.—All Ca/Mg ratios presented here are weight ratios.

organisms can have as low a Ca/Mg ratio, the secondary dolomitization (diagenetic and epigenetic) is probably also very important in their origin. In addition, the Ca/Mg ratio of numerous limestone samples analyzed by the writer, and which are composed almost entirely of the skeletal and protective structures of organisms, exceeds 16:1.

Wide variation of Ca/Mg ratio over short distances indicates epigenetic, secondary dolomitization. The possibility of direct precipitation of highly dolomitic limestones is not excluded.

4. *Dolomitic limestones* (*Ca/Mg=16–60*). The majority of dolomitic limestones of this class have their origin in the accumulation of protective and skeletal structures of organisms. Fine-grained limestone paste present in these limestones is either of chemical origin or has resulted from comminution of skeletal structures of organisms. Partial diagenetic and epigenetic dolomitization is also possible.

5. *Slightly dolomitic (or magnesian) limestones* (*Ca/Mg=60–105*). The upper limit of Ca/Mg ratio of slightly dolomitic limestones is taken as 105. The reason for the selection of this figure is the fact that Ca/Mg ratio of 105.2 is the highest known ratio for calcitic organisms (Oyster). These limestones are also probably the result of accumulation of skeletal structures of organisms. The fine-grained limestone paste of slightly dolomitic limestones is often of chemical origin.

A preliminary investigation conducted by the writer indicated that the fine-grained limestone paste of chemical origin is more homogeneous (chemically) and contains less organic matter than does the fine-grained paste resulting from the comminution of organic debris.

6. *Calcitic limestones* (*Ca/Mg>105*). The calcitic limestones could result from accumulation of skeletons of aragonitic organisms, from direct chemical precipitation, or from subsequent loss of $MgCO_3$. Calcitic organisms have made considerable contribution to some limestones of this group. The high over-all Ca/Mg ratio of these limestones, therefore, is probably due to the low magnesium content of cementing limestone paste, precipitated directly out of sea water. Another explanation is a possible deficiency of ancient calcitic organisms in magnesia.

The possibility of "dedolomitization" should not be disregarded in examining calcitic and dolomitic limestones. Russian geologists report widespread occurrence of "calcitized" dolomites (Tatarskiy, 1949). Dedolomitization converts fine-grained and permeable dolomites into dense, cavernous varieties of calcitic and dolomitic limestones. In such cases one can find inclusions and lenses of fine-grained dolomite and dolomitized fossils inside a calcite matrix. Dedolomitization sometimes also imparts a brecciated appearance to limestones. One of the main reasons why there are few reported dedolomites, is possibly the fact that many field observations of limestones by geologists are only "skin deep," and the dedolomitized limestones have not been recognized.

In classifying limestones and dolomites by this method the Ca/Mg ratios should not be determined from weathered samples collected from the surface of outcrops, because, as shown by the writer (Chilingar, 1956, p. 17), the Ca/Mg ratios of weathered and unweathered portions of the same limestone are markedly different. Also, samples containing numerous cracks should be discarded. The depth of weathering varies from 1 to 2 inches in its effect on Ca/Mg ratio observed by the writer.

A high content of insoluble residue may give a lower Ca/Mg ratio because of the larger amount of magnesium in clays; therefore, clays should be properly separated.

CONCLUSIONS

The classification of limestones and dolomites on the basis of Ca/Mg ratios appears to be a very convenient and practical method, with some divisions dictated by the mode of formation.

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FIGS. 1–2, JUNE, 1957

STUDIES ON BACTERIAL PRECIPITATION OF CARBONATES IN SEA WATER

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ABSTRACT

Carbonates have been obtained in the form of films at the surface of aquarium cultures containing mud from the bay of Villefranche sur mer (Alpes maritimes, France) and sea water enriched with glucose to hasten the bacterial development.

In order to establish the best conditions of formation of this film, I tried to vary the different factors susceptible of variation in nature, i.e. light, temperature, concentration of organic matter, and cultures have been made with sea water concentrated by evaporation (with an extent to salt marshes).

Analyses of the sea water during the experiments have been made to try to determine the process of the formation of the carbonates.

A brief mineralogical study of the films obtained has been made including microscopical analysis, chemical analysis for Ca and Mg, and some X-ray diagrams.

INTRODUCTION

In "Marine Microbiology" ZoBell (1946) indicates the principal theories on the precipitation of calcium carbonates in sea water by bacteria, giving three main hypotheses:

1.—According to Nadson (1928) and Moberg (1934), the production of ammonia by the alteration of proteinaceous material results in an increase of the pH which promotes the precipitation of carbonates.

2.—Nadson (1928) indicates that the reduction of sulfates is a necessary condition for the precipitation of carbonates.

3.—Several authors such as Drew (1910) and Kellerman and Smith (1914) attribute the precipitation to a specific bacteria called *Bacterium calcis* or *Pseudomonas calcis*.

From another point of view, authors studying calcareous muds, such as the Great Bahamas muds or others, tried to explain the phenomenon exclusively by a variation in the physico-chemical conditions. Concerning this last theory, and among a great number of workers, we may note the names of Black (1933) and Smith (1940, 1941), but if Smith excluded completely the possibility of a bacterial activity, Black indicates that the physico-chemical hypothesis and the bacterial hypothesis are both worthy of consideration.

Such are the leading hypotheses. Limitation of space will not allow for a more extended enumeration of the bibliography.

METHOD OF EXPERIMENTATION

During experiments on the preservation of mud samples rich in H_2S from Villefranche sur mer (A.M.), in order to determine the quantities of sulfide, I have been led to try their preservation under zinc acetate, as indicated in the "Standard Methods for the examination of Water and Sewages." After a time, the samples kept under zinc acetate seemed to show a greater effervescence with hydrochloric acid than those kept under mere sea water.

It came to my mind that this was a beginning of the phenomenon—which has not yet been clearly elucidated—of the precipitation of carbonates by mud bacteria in the presence of large quantities of organic matter. That is why I carried on the experimentation until I was able to obtain, at will, different quantities of carbonates.

Founding myself upon the principles of "ecological bacteriology" recommended by S. Winogradsky (1947), I wanted (considering the mud and the sea water as a bacteriological unity) to stray from the usual techniques which consist in isolating pure bacterial species and studying their particular comportment in synthetic media. Those techniques have a great interest from a bacteriological point of view but are of little interest to the oceanographer or the geologist. The main problem for us is the result of bacterial interactions in the marine environment itself.

With this end in view, I utilized the aquarium cultures, and I simply tried to give to the bacteria, in view of hastening their development, only an organic substance easily assimilable. For the first experiments I chose glucose, which is commonly used in bacteriological researches as an enriching substance.

OBSERVATIONS

If in an aquarium containing about 1 Kg of black mud (euxinic mud coming from the swallow-hole of the baie de Villefranche), is added 3 or 4 liters of sea water containing 0.5% of glucose, after 3 days a light irridescent film appears at the surface; the day after, the liquid becomes turbid and the culture emits a strong smell of fermentation, attended with a more or less important escape of gaseous bubbles. As soon as the escape ceases—about the 8th day of culture—the film is much more evident and it is ochre-colored. If taken out, it shows great effervescence with HCl and a very strong reaction with KCNS. It is therefore essentially composed of carbonates and iron, with a light organic support.

Afterwards, the liquid blackens; this coloration is due to the presence of very small black particles suspended in the medium. Those particles are soluble in hypochloric acid, with an escape of hydrogen sulfide (they must therefore be considered as monosulfide of iron). A strong smell of hydrogen sulfide is escaping from the aquarium, while a crystalline film, white and solid, is forming. It is completely soluble in hypochloric acid with effervescence.

In an aquarium containing 3 liters of sea water, if the film is taken out every time it is well formed, the formation begins anew and may be seen during a little more than a month, when the operation takes place in daylight and at the temperature of the laboratory.

At the end of the experiments, and when the aquariums are placed in full sunlight, we may observe—at first in the mud, and afterwards in the whole of the liquid—a very great development of purple bacteria (thiorhodobacteria).

The purple bacteria are only responsible for the removal of H_2S. This phenomenon is a convenient indication of the end of the carbonate precipitation.

A blank experiment, performed in an aquarium containing the same amount of mud and sea water, but without addition of glucose or any nutritive salt, shows no evolution.

Hypothesis on the Formation of Carbonates

The study of the general phenomenon allowed me to build an hypothesis on the formation of carbonates by bacteria.

The accelerated development of the various bacteria of the mud and sea water by the addition of glucose yields an abundant escape of CO_2, whence the smell of fermentation that may be observed during the first days of culture. Afterwards, the sulfate-reducing bacteria set to work, causing an abundant escape of H_2S. This H_2S is partly fixed on the iron hydroxide which has emigrated toward the surface, the rest of it being lost into the air. This escape of H_2S leads to an increase of the pH value; whence the magnesium and calcium ions, free in a medium saturated with CO_2, give a formation of bicarbonates, then, at the water/air interface, where the CO_2 tension decreases, a formation of crystalline carbonates.

ANALYTICAL RESULTS

I have proceeded to a number of measurements to support this hypothesis, namely:

1) pH measurements.
2) Determination of the quantitity of SO_4 ions.
3) Determination of the quantity of H_2S dissolved in the water.
4) Determination by weighing of the quantity of carbonates formed.

The results are recorded in figure 1; one may see that the pH decreases quickly during the first days of culture, in good correspondence with the abundant escape of CO_2. Afterwards, the pH increases quickly up to a value of about 7, then slowly, to reach 8.4 at the end of the experiment.

The quantity of SO_4 ions, which has remained constant for about 12 days, de-

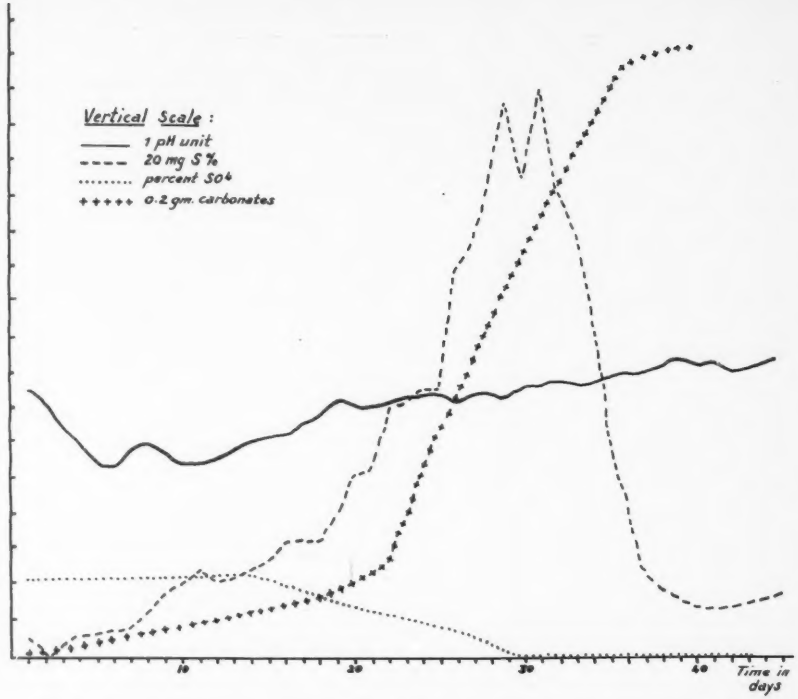

FIG. 1.—Graph showing pH, the evolution of H_2S, and SO_4, and the formation of $CaCO_3$ during the cultures.

creases abruptly and is completely null after 30 days of incubation.

The dissolved H_2S follows evidently an opposite evolution; it begins to increase when the sulfates begin to decrease, reaches its maximum when the sulfates are null, then slowly decreases to be practically null after about 45 days of culture.

The carbonates are formed with a slight delay on the evolution of the sulfates; they begin to crystallize a few days after the beginning of the decrease of the sulfates and stop their formation a few days after the annulment of the sulfates.

In subsequent culture experiments, I have determined the concentration of Ca and Mg in the sea water during the formation of the film; during the first period, i.e. the period of rapid decrease of the pH, I obtained a considerable increase in the concentration of the Ca (from about 0.44 gm/liter to 0.85) and an insignificant increase in magnesium.

In consequence, the hypothesis I proposed is partly confirmed, but during the beginning of the evolution, a dissolution of a part of the calcium carbonate of the mud has taken place; whence the origin of the calcium of the formed carbonates is not only in the sea water, but also in the mud itself.

MINERALOGICAL STUDY

From a mineralogical point of view, the films successively collected present the following characteristics:

The first films are poorly crystallized and are essentially formed by a confused microcrystallization overgrown with iron hydroxide; then, in the next crystallizations, the microcrystallization gives place to spherulites

better and better formed. Very fine growing zones can be seen and in polarized light, the spherulites show perfect black crosses (fig. 2). Those spherulites crystallize so long as the film is forming quickly; when the film is thick, they become coalescent and assume, owing to lack of place for their development, a polygonal structure.

Afterwards when the growth of the film slackens, we observe a simultaneous formation of microcrystallization and of well-formed crystals (sometimes perfect rhombohedrons) and the crystallization ends with microcrystallization only.

The study by X-rays, which have not yet been carried out very far, gives, however, some interesting results. It seems that the microcrystallization and the fine crystallization are formed of calcite, that the spherulites are generally formed of aragonite, and that in the last films dolomite appears.

Measurements in course of the Ca and Mg content of the films show that the films are never pure, they never contain more than 80% of $CaCo_3+MgCO_3$. And in the first and last films they may contain no more than 30% of carbonates. If now impurities are not taken into account and if the magnesium is calculated as dolomite Ca, $Mg(CO_3)_2$ it rarely exceeds 30%, against 70% of pure $CaCO_3$. The conditions of formation of the dolomite have not yet been established.

VARIATION OF DIFFERENT FACTORS

After thus establishing the general phenomenon, I tried to determine, by the same methods, the best conditions for the formation of carbonates in nature. With that end in view, I tried to vary the different factors susceptible of variation in nature.

Aquarium cultures have been made parallelly in alternate daylight and dark, in continuous light and in continuous dark. Only the cultures in the dark gave no film of carbonates, though an important decrease of sulfates was verified.

Cultures have been made at different temperatures. The conclusion is that the best temperature is about 35°C. Above 50° the bacteria are destroyed.

All organic matter containing carbon gave a production of carbonates; the matter containing nitrogen only as peptone or urea gave no results. Utilizing as nutritive substance "Joseph paper" (i.e., pure cellulose) I obtained carbonates, the only difference being in the rapidity of evolution. In fact, the paper had first to be decomposed by the cellulolitic bacteria to become assimilable for the other bacteria. To verify my first hypothesis, I enriched a culture with zinc acetate, and I obtained carbonates.

Different concentrations of glucose have been tried also. Weak concentrations (from 0.1 to 0.4%) do not give a sufficient escape of CO_2, and afford only an incomplete crystallization. Too strong concentrations (above 1%) do not prevent the formation of the film but delay the process: the important escape of CO_2 which makes the medium too acid during a much longer time is responsible for this delay.

To verify the bacterial origin of the phenomenon, cultures have been made at different degrees of sterilization.

Cultures with sterile mud and sterile water with glucose have given no results. Cultures with sterile mud and non-sterile water with glucose gave only a slight crystallization, while cultures with non-sterile mud and sterile sea water with glucose gave a complete crystallization. Accordingly, the phenomenon is bacterial and mud is richer in those bacteria than sea water (although the latter contains a certain quantity of them). Tests have been made with sea water enriched with sulfates. If the culture is enriched with glucose in the same proportion, a greater quantity of carbonates is obtained. Cultures with concentrated sea water and with samples coming from salt marshes, have given no satisfying results, the increase of chlorinity probably having (above a certain point not yet verified) a toxic effect on bacteria.

In order to obtain a beginning of generalization of the phenomenon, I tried to renew it with muds of different origins. The offshore muds of the Mediterranean (blue muds) as well as coastal oceanic muds (La Rochelle) gave satisfactory results.

SUMMARY AND CONCLUSIONS

The hypothesis of the formation of carbonates by the action of bacteria in sea

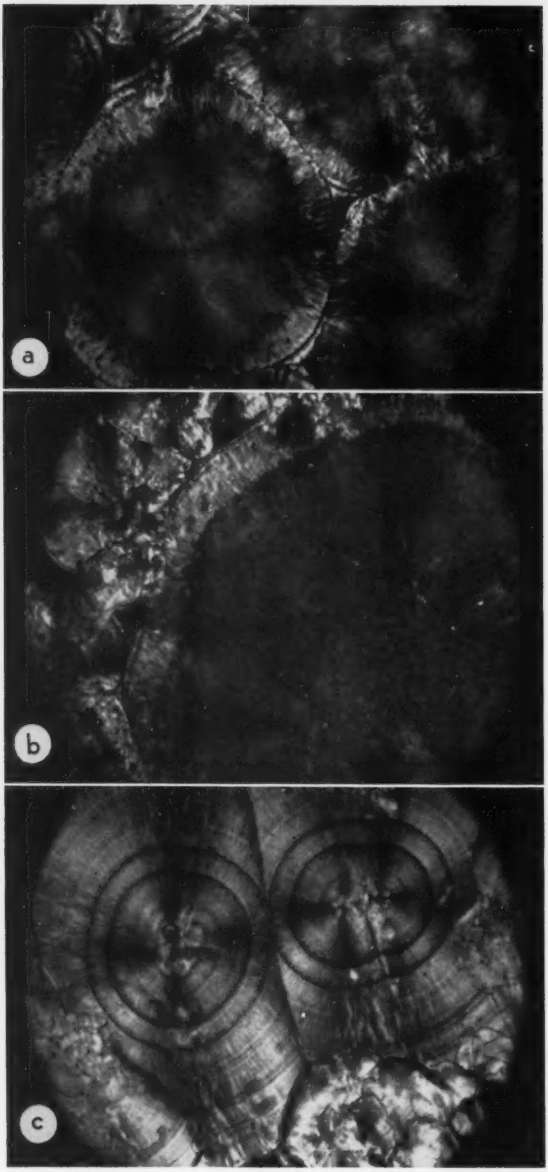

FIG. 2.—Microphotographs of films (×450). a and b, carbonate spherulithes obtained after 22 days of incubation. c, carbonate spherulithes obtained after 32 days of incubation.

water and marine sediments is thus established.

It seems that the formation of carbonates may be obtained from any sediment if the following conditions are fulfilled:

1.—Presence of assimilable organic matter in sufficient quantity.
2.—Temperature sufficiently high.
3.—Maximum light and sunshine; it appears that the phenomenon must take place in shallow waters.
4.—Quiet and very seldom renewed waters. Those conditions are to be found in the lagoons and the portions of sea water most isolated from the open in the tropical seas.

In my opinion, these experiments showing the bacterial origin of carbonates do not exclude the physico-chemical hypothesis. In fact, it seems that the role of bacteria in this case is only to change the physico-chemical conditions of the medium, increasing its concentration of CO_2 up to saturation, enriching it in calcium and giving an escape of H_2S by reducing sulfates. The effect of such reactions is to change the alkaline reserve of the medium, the pH, and so on.

At the end of this study a problem remains unsolved, the part of iron in the phenomenon. The migration of iron which is obtained at the beginning of all the cultures must be due to the action of iron bacteria; this iron concentrated in sea water must play the part of a buffer in the following stages of the experience, fixing a part of the liberated H_2S.

This phenomenon, which is generalized, could explain the frequent associations between iron and limestone in nature. The presence of unstable iron monosulfides, at a certain moment in the cultures, allows us to account for the formation (in certain further conditions of temperature, pressure, and anaerobiose) of the pyrite which is sometimes found in calcareous sediments.

The formation in those cultures of very well-formed spherulites leads us to think of a comparison with oolithic limestones, frequently associated with iron.

Those experiments might explain the still unknown origin of calcareous sediments without any organism or fragments of organisms, such as the matrix of chalk.

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DISCUSSIONS

RELATIONS OF GYPSUM AND ANHYDRITE

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In an article on the Sulphur Series of Sicily, in the March issue of this journal Ogniben (1957) raises some questions about regeneration of anhydrite and integration of gypsum as presented by me in Memoir 50 of the Geological Society of America (Goldman, 1952). These and some other points I would like to discuss briefly.

Regenerated Anhydrite

Ogniben objects to the term regenerated as too limited and proposes epigenetic instead because gypsum that was primary can go over to anhydrite. Epigenetic is the more inclusive term and could have been used in my report. But I think regenerated is a more specific, informative, and vivid term for the particular epigenetic ahnydrite I was describing. This anhydrite can be seen, in large part, as syntaxial growths around corroded anhydrite crystals in gypsum. The gypsum in which this anhydrite develops was therefore itself derived from pre-existing anhydrite. I hope that in the final report that Ogniben promises he will illustrate epigenetic anhydrite formed in primary sedimentary gypsum. It will be interesting to see how it differs from that formed in the presence of remnants of original anhydrite and, in general, in gypsum derived from hydration of anhydrite.

In that connection it should be pointed out that the frequency, in thin sections of regenerated anhydrite, of crystals of low birefringence or "oblique to the optical axes" (Ogniben, p. 67, column 2) is not necessarily a characteristic of regenerated anhydrite but is, as pointed out in Memoir 50 (p. 63, item (4) and p. 64, item (10)), probably related to stresses in the cap rock combined with the orientation of thin sections.

Integration

More vital issues are involved in this topic, but to dispose of nomenclature first, it seems to me that integration is a correct term for the growth of larger crystals from an aggregate of smaller ones and an adequate equivalent for the German "Sammelkristalisation." It is true that the process I have suggested is different from what Rinne had in mind for "Sammelkristalisation." But either term (Sammeln = to gather, collect) seems to me inclusive enough to cover the process involved however it takes place. Ogniben is in error in stating that I apply integration to the particular process of integration of gypsum that I have suggested. I intended it as an equivalent of "Sammelkristalisation."

The real issue involved concerns irregularly bounded areas of gypsum of complex internal structure and complexly interrelated. Ogniben calls them superindividuals and attributes them to fracturing of larger preexisting selenitic gypsum crystals. I regard them as stages in the development of large, clear, selenite crystals by integration of aggregates of small gypsum grains.

I admit that, in the absence of supporting evidence, I arrived most hesitantly at the suggestion that integration took place in gypsum by interorientation at a distance in an aqueous medium, but I saw no other way of explaining the observed phenomena. In support I can only refer again to the discussion on pages 13 to 15 of Memoir 50 where the reverse process that Ogniben discusses, crushing of pre-existing selenitic gypsum, is also considered.

Large crystals of gypsum grading at the borders into fine-grained aggregates, such as are illustrated in figures 5 and 6 of Ogniben's article, are what would be expected in the production of fine-grained masses from whole crystals (though even here some recrystallization of fine border material may have taken place, as suggested by the patch of fine-grained gypsum, nearly surrounded by selenite, in the top center of figure 5). I found nothing even vaguely resembling this in cap rock, nor the "intergranular zones of fine grains" that Ogniben himself says should be expected. Ogniben, as I understand him, found this type of relationship only in his Sulphiferous Series which, according to him, was not subjected to great pressure. There, he assumes, it was formed by movement between selenite grains as a result of expansion due to change from anhydrite to gypsum. There is little or no evidence of such volume increase in the

material described in Memoir 50 (see p. 10–11).

In his figures 8 and 9 Ogniben illustrates what he calls superindividuals that seem identical with stages in the sequence that I have described as integration—stages between say, figure 3 and figure 2 of plate 8, of Memoir 50. He records the absence of "limpid selenite cores." and the absence of definite boundaries in his figures 8 and 9 as in the specimens from which the two figures of plate 8 of Memoir 50 were taken.

I must dissent fundamentally from Ogniben in his interpretation of the material illustrated in his figure 10. This is apparently intended to show bodies of finely crushed gypsum derived from the well-integrated gypsum in which they lie. To me it seems to illustrate not "anastomosing vein-like gypsum . . . *surrounded* [emphasis mine] by a homogeneous gypsum aggregate" of fairly uniform grain size, but gypsum-filled *shear zones* penetrating a homogeneous fine-grained gypsum aggregate such as I have called "primary unintegrated gypsum" (Memoir 50, p. 11, and plate 6, figure 1). The "fluidal structure" (Ogniben, p. 74) of the fine-size aggregate conforms to this interpretation. In their degree of integration ("vein-like patches belonging to one superindividual," Ogniben, figure 10) the "veins" seem to resemble those in the specimen of Plate 9, figure 5 of Memoir 50, though those are in anhydrite. Coarse-grained, less integrated shear zones of gypsum in fine-grained gypsum are illustrated in plate 12, figure 2 of Memoir 50.

If the highly integrated gypsum of the veins in Ogniben's figure 10 formed along shear zones then the finer grained gypsum bodies between them must be older than the gypsum veins and not a crushed part of the gypsum of the veins. The effect of shearing stress in promoting recrystallization (in this case integration) (Memoir 50, p. 25) would explain the larger gypsum units along the shear zones, with residual fine-grained gypsum bodies between.

The shearing that produced this pattern of "veins" may be due to the diapiric uplifts to which Ogniben refers (p. 66, column 1).

The fundamental problem that Ogniben has failed to solve is the absence of evidence of Sammelkristalisation of the type defined by Rinne. He does not illustrate, and I did not find, stages in which, in fine-grained gypsum, there were distinct well-defined single crystals successively larger and more dominant in successive stages, ending in secondary selenite crystals of the type illustrated in Ogniben's figures 5 and 6. It was the absence of these stages that led me to seek some other explanation for the development of large clear selenite crystals. Integration by the process that Rinne had in mind is what I assumed took place in the anhydrite of the cap rock.

Whatever explanation of Sammelkristalisation or integration in gypsum may ultimately prove to be right, it is necessary to remember that neither of us has seen any transformation actually take place, and that we are both arranging observed facts in the sequence which to us seems plausible, Ogniben's in one direction, mine in the opposite. Further observation, and perhaps experiment, should establish which interpretation is the correct one. Perhaps there is some truth in each.

Some minor points should be mentioned.

It is coming to be generally agreed that the gypsum-anhydrite cap rock of salt domes is the product of residual accumulation, by solution of the salt of salt stocks, of the anhydrite distributed through the salt (Goldman, 1933; Harrison, 1956). The cap rock can therefore not be considered Paleozoic (Ogniben, p. 77, column 2).

From this it follows that there are probably considerable differences in the history of the sulfur deposits in cap rock and those in the sedimentary deposits of Sicily (Ogniben, p. 66–67), though the processes in each may be related.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 2, PP. 198–201
FIGS. 1–2, JUNE, 1957

A FABRIC AND PETROLOGIC STUDY OF THE PLEASANTVIEW SANDSTONE

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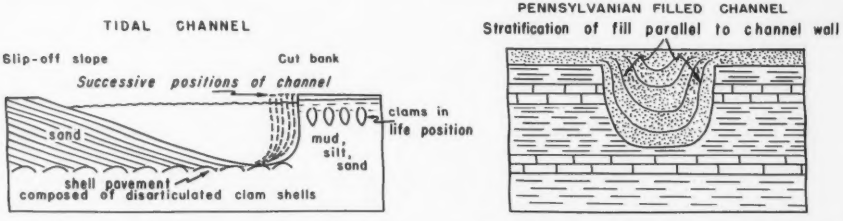
In the March, 1957, issue of the *Journal of Sedimentary Petrology* (v. 27, p. 41–55), Gene A. Rusnak describes the fabric and petrology of the Pleasantview Sandstone (Pennsylvanian) of west-central Illinois, the basal member of the Summum Cyclothem. This sandstone occupies channels cut into underlying sediments for as much as 80 feet locally, whereas outside the channels the Pleasantview unit is much thinner and rests concordantly on the beds below. A notable feature of the sandstone filling the channel is the initial dip of its stratification, which in areas close to the margins of the channel is parallel to the channel walls. Stratification becomes horizontal, however, in the central parts of the channel (p. 43–44). Rusnak infers this relationship suggests the channel filling material came from outside the channel, rather than from aggradation by a stream flowing within the channel (compare with Weller, 1956, p. 29). Similar initial dip has been reported from other channels in Illinois and from filled sinks (Ekblaw, 1931; Bridge, 1955, p. 728, pl. 1).

In view of this relationship, Rusnak compares the conditions of deposition of the Pennsylvanian Pleasantview Sandstone with those prevailing in the modern Wadden Sea off the northern coast of The Netherlands, as described by van Veen (1950) and van Straaten (1951; 1952; 1954a; 1954b). In particular Rusnak refers to the distinction emphasized by van Straaten (1951, p. 236–238, 243; 1952, p. 500–502, fig. 1; 1954a, p. 26–27, fig. 3; 1954b, p. 7–8, fig. 4) between the horizontal stratification produced by "vertical sedimentation" where fine material settles out of suspension on mud flats between the tidal channels and gullies which traverse the tidal flats, and the gently inclined stratification produced by "lateral sedimentation" on forward-growing point bars on the inside of meander curves in channels and gullies as the channels shift laterally. Rusnak (p. 43–44) evidently considers the inclined strata of the channel filling to be analogous with the inclined stratification of the point bars of van Straaten's "lateral sedimentation." The present writer questions the validity of this comparison, as explained below.

The following sketches (fig. 1) illustrate the two conditions of sedimentation under



A. Schematic cross section through a meander of a Recent tidal channel, showing how lateral shifting of channel causes reworking of tidal flat sediments of the cut bank (deposited by "vertical sedimentation") and their redeposition by "lateral sedimentation" on the slip-off slope. (Suggested by figures in Van Straaten, 1951, 1952, 1954 a, 1954 b).

B. Schematic cross section of filled channel in Pennsylvanian strata of Illinois, showing truncated horizontal stratification of underlying marine shales and limestones and sandstone fill of channel, with stratification parallel to channel walls. (Suggested by figures and text of Rusnak, 1957).

FIG. 1.—Comparison between Recent tidal channels of Wadden Sea, N. W. Holland (A) and filled channels in Pennsylvanian strata, west-central Illinois. (B) (Not drawn to scale.)

consideration, A representing the "lateral sedimentation" of the channels and gullies on the Wadden Sea tidal flats as described by van Straaten, and B representing the filled channels within the Pennsylvanian strata of Illinois described by Rusnak. The characteristic feature of "lateral sedimentation" is the destruction of horizontal stratification on the cut bank (receding bank) by lateral shifting of channels and its replacement by inclined stratification on the slip-off slope (point bar or prograding bank). Material of all sizes found in the cut bank is sorted by this lateral migration of the channels: shells and any coarse sediment accumulate as a lag pavement on the channel floor, sand collects on the point bar, and mud is generally washed away by the water in the channel. These processes take place while the channel is open to flow of water; in fact, it is the flow of water in the open channel which motivates the action. In the Pennsylvanian rocks of Illinois, by contrast, the stratification of the units cut by the channel is horizontal right up to the channel margins (Rusnak's fig. 1), and the stratification of the sand filling dips toward the axis of the channel in accordance with the slope of the channel wall. If any sediments in the Pennsylvanian are analogous to those deposited in the Wadden Sea by "lateral sedimentation" it is those on one or the other side of the channel, but outside the limits of the channel. In view of the composition and truncated horizontal stratification of the marine shales and limestones cut by the channel and the lack of evidence of lateral shifting of the channel itself, the present writer rejects Rusnak's comparison with the Wadden Sea and proposes instead to adhere to the idea of Weller (1956, p. 29) and Rusnak that the channels were cut at one time and filled in from the sides at a slightly later time, perhaps but not necessarily, by a different mechanism from that which cut the channels.

The channels at the base of cyclothem units are generally considered to be products of subaerial fluvial erosion[1] of newly uplifted marine sediments which were deposited during the marine part of the preceding cycle (Weller, 1956, p. 26). In contrast, Rusnak rightly points out that these channels might have been cut by tidal currents (p. 51). By implication from his comparison with the Wadden Sea, one must suppose that he regards the sand channel filling, also, to be of marine origin, having been swept in from tidal flats or nearby beaches or shallow sea floor. That this might be true in some instances is suggested by reported occurrences of marine fossils in the basal unit of the cyclothem (Weller, 1956, p. 28). In spite of the reported marine fossils, however, Weller (1956) believes it is a valid generalization that all lower beds of a cyclothem are nonmarine.

As is well known, tidal channels can be cut deeply into unconsolidated sediments;[2] the importance of this mechanism in creating channels should not be overlooked. In working out geologic history, however, the overlying strata should be consulted to determine the fluvial or marine origin of the channels and their subsequent filling. As the channels may be either of tidal or fluvial origin, and the filling likewise of either origin, several combinations are possible: (1) tidal channels—littoral marine filling, perhaps indicating subsidence but no particular changes in geography; filling sediment of marine origin, (2) tidal channels—fluvial filling, indicating marine regression between cutting and filling; filling sediment nonmarine, (3) fluvial channels—fluvial filling, indicating a change in stream regimen from cutting to filling; filling sediment nonmarine, (4) fluvial channels—littoral marine filling, indicating marine transgression; filling sediment should contain marine fossils.

As the basal channel sand of the cyclothem generally passes upward into coal de-

[1] Wanless and Shepard (1936, p. 1202) suggested the channels "may have been cut in part below sea level, just as the Amazon, Mississippi, and other large rivers have cut their channels one hundred feet or more below sea level where they cross their deltas," but nevertheless associated channels with rivers.

[2] A particularly fine example of the results of tidal scouring is shown in the northwest corner of the Island of Walcheren, in southern Holland. Most of the island lies below mean sea level, having been reclaimed by diking off the sea. When the R. A. F. bombed the dike at Westkapelle in 1945 nearly all the island was inundated by a few feet of salt water. The back and forth movement of the tides through the constricted opening scoured a channel 20 meters deep. When the dike was later repaired, a small, deep lake remained behind it. This lake, marking the position of the old tidal channel, has not been filled in, but is kept as a recreation area.

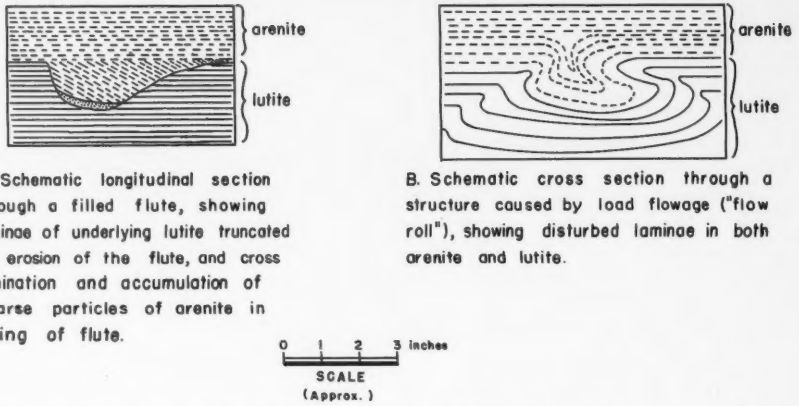

arenite
lutite
arenite
lutite
A. Schematic longitudinal section through a filled flute, showing laminae of underlying lutite truncated by erosion of the flute, and cross lamination and accumulation of coarse particles of arenite in filling of flute.
B. Schematic cross section through a structure caused by load flowage ("flow roll"), showing disturbed laminae in both arenite and lutite.
0 1 2 3 inches
SCALE
(Approx.)

FIG. 2.—Comparison between filled flute (A) and "flow roll" (B), showing difference of lamination in arenite and lutite. (Suggested by figures in Kuenen, 1953b.)

posits, the filling sediment is doubtless nonmarine in most instances, though the channel could be of either tidal (alternative 2) or fluvial (alternative 3) origin.

Rusnak's use of the term "flow rolls" also evokes comment Referring to certain protuberances on the base of the sandstone beds, Rusnak writes:

". . . the undersurface of the sandstone disclosed markings, resembling minute ripple marks, similar to those described as 'groove casts' by Shrock (1948, p. 163–165) and attributed to subaqueous scour by Rich (1950) . . . Groove casts appear to be associated with gentle wall slopes. With steep wall slopes, however, a lobate form of cast is more common (fig. 4). Rich (1950) calls such lobate forms 'flow rolls' and describes them also as scour marks. Along the eastern border of the channel the orientation of both grooves and lobe casts is down the channel walls to the southwest. Hence, if scour formed these marks, the scour was directed towards the channel from northeast to southwest along the eastern border . . ." (p. 42–43)

This seems a clear misapprehension of Rich's remarks. Rich (1950, p. 727) showed how certain markings, to which he applied the term "fluting" (after Maxson and Campbell, 1935) and also called "flow marks," now preserved as casts on the base of the overlying bed, are the result of bottom scour by a sediment-laden current. But Rich also added:

"It seems, however, that not all so-called 'flow-roll' markings on the underside of silt or fine sandstone beds are the result of abrasion of the underlying muds by running water. Some of them seem to be due to internal movements in the unconsolidated silt beds, causing them to roll down into the muds below, as was thought by Fuchs (1895)." (Rich, 1950, p. 727)

Rich clearly did not apply the name "flow roll" to all such marks, as implied by Rusnak, but rather cites this term within quotation marks as being one in current use. Rich also sets forth the distinction between bottom-scour marks and the results of load flowage of unconsolidated sediment (which produces the "flow casts" of Shrock, 1948, p. 156, later called "load casts" by Kuenen, 1953a, p. 1058). The distinction between structures formed by these two processes has been clearly set forth by Kuenen (1953b, p. 23–25); it entails study of the laminae both within the protuberance and outside it in the adjacent lutite, as illustrated in the accompanying sketches (fig. 2).

Rusnak's figures 5 and 6 portray masses of contorted arenite which have been enveloped in their entirety by lutite after hydroplastic flow. Rusnak's figure 4 also suggests protuberances formed by load flowage, but in the absence of the evidence of the internal and external lamination, one cannot be certain.

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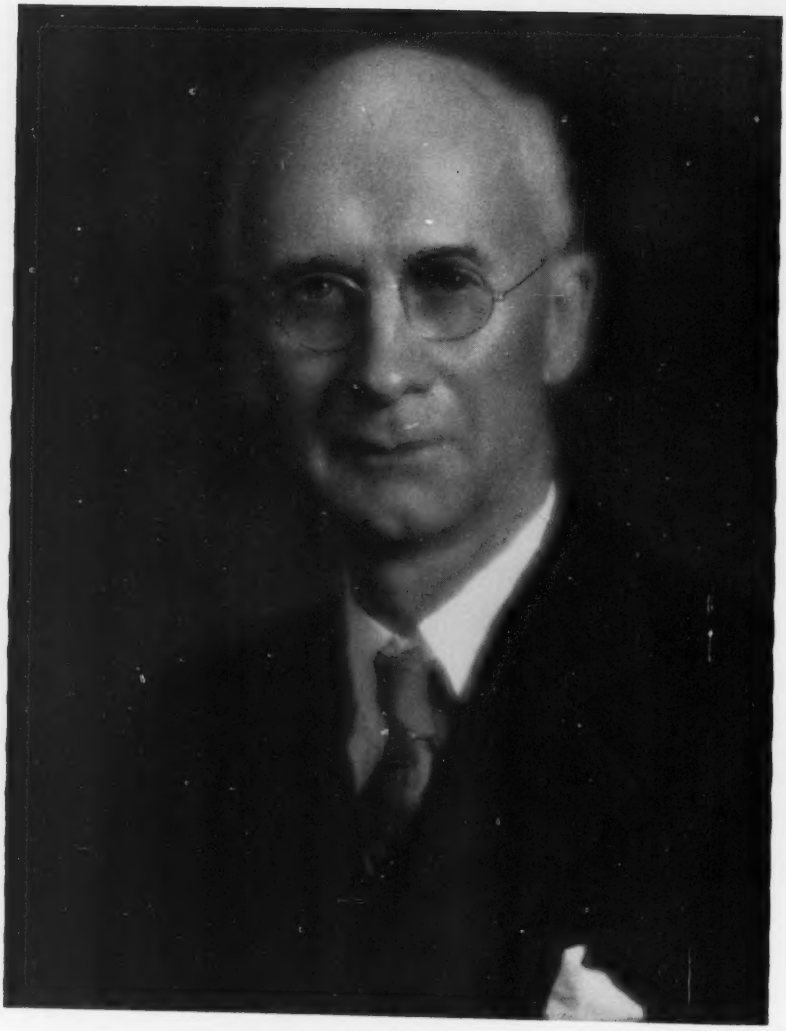

William Henry Twenhofel

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 2, P. 203
JUNE, 1957

MEMORIAL TO WILLIAM HENRY TWENHOFEL[1]
(1875-1957)

ROBERT R. SHROCK

William Henry Twenhofel, dean of American sedimentologists, child of the fossiliferous shale hills of Kentucky across the Ohio from Cincinnati, student of Schuchert and disciple of Barrell, taught thousands of students at Kansas and Wisconsin, and after retirement, at Yale and the University of Tulsa. He reached many more thousands through his writing, and profoundly influenced sedimentology and stratigraphy in North America for a generation.

Possessed of driving ambition, strong personal discipline, and almost incredible energy, he was a devoted scientist who, once committed, went where he needed to go, did what had to be done, and completed the assignment. His record of professional service and of published works is his monument to this devotion.

His was the creed and the attitude of a past generation. He accepted frugality as a way of life, long hours and hard work as a prerequisite of self respect, service to his profession and to his science as an inescapable responsibility, and loyalty to his friends and to truth the unquestioned obligation of man, teacher and scientist.

As scientist speaking before his peers, he commanded their respect, and meeting with them in committee he received their cooperation when it was requested, because they knew he never asked anyone to work harder or to do more than he himself was prepared to do.

He was at his best when lecturing to undergraduate students, and many a successful petroleum geologist has him to thank for a thorough grounding in the fundamentals of geology. He had deep respect for the teaching profession and a strong sense of responsibility to the student to give him the best possible training in whatever subject he happened to be teaching.

He has been a bulwark of strength in the Society of Economic Paleontologists and Mineralogists since its founding. For the first two years, as one of the associate editors, he assisted Raymond C. Moore, editor, in getting the *Journal of Sedimentary Petrology* launched; then for the next eighteen he served as editor, and by the end of this score of years he had brought our *Journal* to the highly respected position it now holds among geological periodicals.

He was our President in 1935 and served our Society in many little noticed but highly important ways throughout his thirty years of membership. His election as Honorary Member in 1949 was recognition of his valuable services to our Society as well as of his distinguished contributions to our fields of interest.

His was a full, active and healthy life, intensely devoted to teaching, investigating and writing. Death came quickly and gently at fourscore years and one to end the work of a great American student of sediments and sedimentary rocks.

[1] This memorial was presented by President Shrock before the Annual Meeting of the Society of Economic Paleontologists and Mineralogists in St. Louis, Missouri, on April 2, 1957.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 2, P. 204
JUNE, 1957

REVIEW

Sedimentary Rocks, by F. J. Pettijohn, 2nd ed., 1957. Pp. xvi+718; figs. 173; pl. 40; tables 119; 6×9¼ in., cloth. Harper and Brothers, New York. Price, $12.00.

Reviews of second editions are often redundant. The author corrects the errata and the reviewer finds a few new ones. Dr. Pettijohn's original *Sedimentary Rocks* has been substantially metamorphosed in its second editing, however, and it is hoped the following comments will be worthwhile even to careful readers and referers of the 1st edition.

The statistical changes involve an increase in number of pages on the same format from 526 to 718; figures increase from 131 to 173; plates remain the same at 40; and the number of tables dropped from 139 to 119. This reviewer is not trying to say the book is 718/526 better than its parent; the numbers are listed to document the size of the change.

The scope of the changes are more significant. Considerable reorganization of the subject matter has taken place. Textures, Composition, and Structures are considered first in both editions. The separate chapter on Color has been dropped in the new edition. The chapter on classification followed by the main rock group chapters—Conglomerates, Sandstones, Shales, Limestones and Dolomite, and Nonclastic Sediments—follow the same order in both editions. The major changes are in the last chapters: Weathering, Transportation, Deposition, Lithification and Diagenesis concluded the original edition. In the new edition the concluding chapters now follow this sequence: Provenance, Dispersal, Depositional Environments, Lithification and Diagenesis, and Historical Geology of Sediments.

Reading these new chapters gives the impression that Dr. Pettijohn feels his aim of the first edition—description and recognition of data contained in outcrop, hand specimen, and thin section, and genetic significance of these data—may have been a bit too narrow. These new chapters lean well into the subjects of sedimentation and sedimentary tectonics. Hand specimens and outcrops are left far behind. This is a positive change, for the subjects of sedimentary petrology, sedimentation, and stratigraphy are so intimately interrelated that to even arbitrarily package them into separate academic parcels is a formidable task.

Dr. Pettijohn's inclusions of all the diverse definitions and opinions of controversial subjects such as graywackes in the original *Sedimentary Rocks* has been stimulating to the academic student, but a bit disconcerting to the practicing geologist seeking a firm or prevailing definition to guide his observations. Dr. Pettijohn's own opinions and definitions are more apparent in the new edition, and it is probable that these will help clarify some of the dilemma.

The increase and new arrangement of bibliographic references by chapter is most welcome. Many new figures have been added, and there is much better coherence between the text and illustrations. The number of plates is the same but several have been cropped to allow more specimens illustrated on each plate. The photomicrographs are of exceptional quality.

If Dr. Pettijohn's Sedimentary Rocks has an easily accessible spot on your bookshelf, it should be replaced by his 2nd edition. He has done a completely new and even more excellent job.

R. W. DECKER
Dartmouth College

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 2, PP. 205–222
JUNE, 1957

SOCIETY RECORDS AND ACTIVITIES

REPORTS AND MINUTES OF THE THIRTY-FIRST ANNUAL MEETING OF THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The thirty-first annual meeting of the Society of Economic Paleontologists and Mineralogists was held in Assembly Hall No. 1 of the Kiel Auditorium, St. Louis, Missouri, April 1–4, 1957, in conjunction with the annual meeting of The American Association of Petroleum Geologists.

The program consisted of a joint meeting with the A.A.P.G., with papers on Recent Sedimentation in Northern Gulf of Mexico being presented. The Society's program consisted of papers on Biostratigraphy; Sedimentary Mineralogy, Petrology, and Sedimentology; Geochemistry of Sedimentary Materials; and Paleontology and Stratigraphy.

The Presidential Address of the Society, "New Geological Horizons," was given by Robert R. Shrock at a joint session on Tuesday, April 2. (For complete address, please refer to A.A.P.G. *Bulletin*, Vol. 41, No. 7.)

Also at the joint session an "Honorary Membership Scroll" was presented to Henry V. Howe and it was announced that Philip H. Kuenen had been elected a Correspondent of the Society.

Born at Fulton, New York, on June 15, 1896, Henry V. Howe received a B.A. degree from the University of Oregon in 1916. He was a fellow at Yale University from 1916 to 1917, at the University of Oregon from 1918 to 1919, and at the University of California from 1919 to 1921. In 1922 he received a Ph.D. degree in geology from Stanford University.

Dr. Howe's experience includes: assistant professor, associate professor, and professor in the department of geology of Louisiana State University. He became the Director of the School of Geology in 1931 and from 1944 to 1949 was dean of the College of Arts and Sciences. In addition, from 1929 to 1927, he was consulting geologist for the Union Sulphur Company and from 1934 to 1940 was director of the research division of the Louisiana Geological Survey.

Howe's scientific affiliations are numerous, including The American Association of Petroleum Geologists, Geological Society of America, Paleontological Society, Geophysics Union, and Louisiana Academy of Science. He is a charter member of the S.E.P.M.; was president pro tempore, 1927–1928; secretary-treasurer from 1937–1939; and president from 1941–1942. Dr. Howe was very instrumental in helping to place the Society on a sound financial status during his two-year term as secretary-treasurer, and it was mainly due to his efforts that a satisfactory agreement with the Paleontological Society was reached for publishing the *Journal of Paleontology* jointly with that Society. Howe has served on numerous S.E.P.M. committees and has published many articles on paleontology in our *Journal of Paleontology* and on stratigraphy in the A.A.P.G. *Bulletin*.

Because of this honor, Dr. Howe will retain a life-time membership in the Society of Economic Paleontologists and Mineralogists and the *Journal of Paleontology* will be sent to him complimentary.

This year (1957) the Research Committee of the Society of Economic Paleontologists and Mineralogists nominated and the Council elected Philip Henry Kuenen of the Netherlands as a Correspondent, in recognition of the outstanding contributions that he has made in several fields of interest represented in our Society.

According to the constitution of the S.E.P.M. (Article 3, Section 5), "Correspondents shall be persons not resident in North America who have made distinctive contributions to paleontology, petrology, and stratigraphy that have application to the geology of petroleum."

In honoring Dr. Kuenen, who is professor of geology at the Geological Institute in Groningen, the S.E.P.M. takes special recognition of his contributions to sedimentation and stratigraphy. Although perhaps best known to American geologists for experimentation with sediment-laden water

HENRY V. HOWE
Elected to Honorary Membership

PHILIP H. KUENEN
Elected S.E.P.M. Correspondent

currents and application of his results to the interpretation of graded bedding and certain other primary structures in sedimentary deposits, Dr. Kuenen has always had a broad range of interest in the problems of the oceans and ocean bottoms. Papers listed in his bibliography concern such subjects as sediments of the deep seas, atolls, submarine canyons, pebble abrasion, ptygmatic folding, origin of volcanoes, relations between submarine topography and gravity field, and numerous articles on the scientific discoveries of the *Snellius Expedition* in the East Indian region.

As author of *Marine Geology* (John Wiley and Sons, New York, 1950), Dr. Kuenen brought together in masterly fashion a great mass of information on the geological aspects of oceans and ocean bottoms, and this outstanding book has become one of the standard works on the subject.

In a more recent book, *Realms of Water* (Cleaver Hume, London, 1955), he has again demonstrated unusual competence in bringing together a vast accumulation of scattered information dealing with a subject of great common interest.

In this imposing array of articles and books on a wide range of subjects, the petroleum geologist turns with deepest interest to Dr. Kuenen's many papers on sedimentary processes and structures published in various journals including the *Journal of Sedimentary Petrology* and the *Bulletin* of the A.A.P.G.; to his contributions to the 1950 (Chicago) S.E.P.M. Symposium on Turbidity Currents and his participation in the 1955 (New York) A.A.P.G. Symposium on the Late Quaternary Geology of Modern Sedimentary Basins; to his monographic contributions to the recent sedimentation in the Dutch East Indies; and to his sponsorship of recent sediment studies in the Orinoco delta area recently published by van Andel and others.

By virtue of his activities as stimulating teacher, ingenious experimentalist, imaginative investigator, and scholarly author, Dr. Kuenen has brought distinction to his country, to himself, and to his profession. In honoring him, the S.E.P.M. also honors itself in electing him Correspondent.

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39. Slumping in the Carboniferous rocks of Pembrokeshire. Quart. Jour. Geol. Soc. London, 104, pp. 365–385, 1948.
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41. Stereoscopic projection for demonstration in geology, geomorphology and other natural sciences. Jour. Geol., 58, pp. 49–54, 1950.

42. The formation of the continental terrace. The advancement of Science, Vol. VII, 25, pp. 76–80, 1950.
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46. Mechanics of varve formation and the action of turbidity currents. Geol. Fören. Förhandl., 73, pp. 69–84, 1951.
47. An argument in favor of glacial control of coral reefs. Jour. Geol., 59, pp. 503–507, 1951.
48. Turbidity currents as the cause of glacial varves. Jour. Geol., 59, pp. 507–508, 1951.
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51. Slump structures in the Waitamata beds around Auckland. Trans. Roy. Soc. New Zealand, 78, pp. 467–475, 1950.
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57. Origin and classification of submarine canyons. Bull. Geol. Soc. Am., 64, pp. 1295–1314, 1953.
58. Recent advances in deep-sea sedimentology. Proc. Roy. Soc., A, 222, pp. 289–295, 1954.
59. Eniwetok drilling results. Deep-sea Research, I, pp. 187–189, 1954.
60. Sea level and crustal warping. Geol. Soc. Am. , Spec. Paper, 62, pp. 193–203, 1955.
61. Realms of water, Cleaver Hume, London, 1955.
62. Recent sedimentation as a key to ancient deposits (*Abstract*), N. Y. Oil Finders Convention, A.A.P.G.-S.E.G.-S.E.P.M. Joint Meeting, Mar. 28–31, 1955, p. 28.
63. The difference between sliding and turbidity flow. Deep-sea Research, 3, pp. 134–139, 1956.
64. Experimental abrasion of pebbles. 2. Rolling by currents. Jour. Geol., 64, pp. 336–368, 1956.
65. Problematic origin of the Naples rocks around Ithaca, N. Y. Geol. en Mijnb., 18, pp. 277–283, 1956.
66. +*J. E. Sanders*. Sedimentation phenomena in Kulm and Flözleeres graywackes, Sauerland and Oberharz, Germany. Am. Jour. Sci., 254, pp. 649–671, 1956.
67. Experimental abrasion of pebbles. 1. Wet sand blasting. Leid. Geol. Med., 20, pp. 131–137, 1955.
68. +*E. ten Haaf*. Graded bedding in limestones. Proc. Kon. Ned. Ak. Wet. Amsterdam, Ser. B., pp. 314–317, 1956.

In addition to the above awards, Research Committee Chairman Curt Teichert, presented the Society's Award for the Best Paper for 1955 in the *Journal of Paleontology* to William R. Walton, for his paper entitled, "Ecology of Living Benthonic Foraminifera, Todos Santos Bay, Baja California," which appeared in the November issue, Volume 29, Number 6. Mr. Teichert also presented the award for the best paper for 1955 in the *Journal of Sedimentary Petrology* to Louis Field Dellwig, for his paper entitled, "Origin of the Salina Salt of Michigan," which appeared in the June issue, Volume 25, Number 2.

The Best Paper Awards are the third to be presented by the S.E.P.M. They consist of a certificate given to the author whose paper, appearing in the Journals during the second preceding year, is judged by the Research Committee to be the most outstanding contribution of the year.

Born at Fort Worth, Texas, November 4, 1923, William R. Walton entered Amherst College, Amherst, Massachusetts, in the year 1946 and received a B.A. degree in geology from that institution in 1949. The next year he attended Harvard University where he specialized in sedimentation. In 1950 Mr. Walton transferred to the University of California's Scripps Institution of Oceanography where he majored in oceanography and received both his M.S. degree (1952) and Ph.D. degree (1953).

In 1953 Dr. Walton accepted a position with the Gulf Research and Development Company, Houston, Texas, the nature of his work being recent ecology, and in the summer of 1956 was transferred by that company to its Pittsburgh office.

Mr. Walton's publications, in addition to his recent article in the *Journal of Paleontol-*

WILLIAM R. WALTON
BEST PAPER AWARD, 1955
Journal of Paleontology

LOUIS F. DELLWIG
BEST PAPER AWARD, 1955
Journal of Sedimentary Petrology

ogy, include, "Ecology of Marsh and Bay Foraminifera, Barnstable, Massachusetts," *American Journal of Science*, Volume 248, April, 1950 (with Fred B. Phleger) and "Techniques for the Recognition of Living Foraminifera," Cushman Foundation for Foraminiferal Research, Volume III, Part 2.

Dr. Walton is a member of Sigma Xi, and in June, 1954, he became an associate member of the Society of Economic Paleontologists and Mineralogists.

Louis Field Dellwig was born February 13, 1922, in Washington, D. C. He entered Lehigh University in the fall of 1939 and obtained both his B.A. and M.S. degrees from that institution in 1943 and 1948, respectively. Later he transferred to the University of Michigan from which he was granted a Ph.D. degree in geology in February, 1954.

During the summers of 1948 and 1949 Mr. Dellwig was engaged in pegmatite studies for the U. S. Geological Survey and from June, 1950, until January, 1952, he was engaged in uranium and thorium investigation for the U.S.G.S. From September, 1951, until June, 1953, Mr. Dellwig was an instructor in general, historical, and field geology at the University of Michigan, and in 1953 he accepted a position with the University of Kansas geology department as an assistant professor of structural geology.

Dr. Dellwig's scientific affiliations, in addition to his membership in the S.E.P.M., include the Seismological Society of America, American Geophysical Union, Geological Society of America, and The American Association of Petroleum Geologists.

In addition to his recent paper in the *Journal of Sedimentary Petrology*, Mr. Dellwig has published an article in the *American Mineralogist*, Volume 38, entitled, "Hopper Crystals of Halite in the Salina of Michigan." Also, Mr. Dellwig is a co-author of "Thorium Investigations, 1950–1952, Wet Mountains, Colorado," which appeared in the U. S. Geological Survey Circular 290.

ANNUAL BUSINESS MEETING

The annual business session of the Society was called to order at 4:00 P.M., Tuesday, April 2, by Robert R. Shrock, president, who introduced the officers for the new year as follows: President, R. V. Hollingsworth; Vice-President, Stuart A. Levinson; Secretary-Treasurer, Samuel P. Ellison, Jr.; Editor of the *Journal of Paleontology*, M. L.

Thompson; and Editor of the *Journal of Sedimentary Petrology*, Jack L. Hough. Shrock remains a member of the council as Past-President.

It was moved, seconded, and carried that the minutes of the 1956 meeting be approved as published in the July, 1956, *Journal of Paleontology* and the June, 1956, *Journal of Sedimentary Petrology*.

The following reports were given:

1. *Report of the Editor of the Journal of Paleontology (W. M. Furnish).*—Volume 30 of the *Journal of Paleontology*, issued in conjunction with the Paleontological Society, contains a total of 1,394 pages and 146 plates. There are 94 titles plus paleontological notes, reviews, and an author-subject index. Society records, notices, and abstracts of meetings are also included.

This volume represents an increase of 210 pages and 38 plates over the preceding one; it exceeds a 10-year average by about 250 pages and 40 plates. That portion of Volume 30 sponsored by the S.E.P.M. (March, July, and November issues), totals 584 pages and 54 collotype plates. These items represent an increase of 90 pages of text and 18 plates over that in corresponding issues of the previous years; and about 70% and 60%, respectively, of Paleontological Society totals in Volume 30. Most manuscripts have been published within nine months after being received, and there has been a rather uniform supply on hand to maintain this margin.

In the S.E.P.M. issues of Volume 30, there are 29 papers, exclusive of notes. Four were contributed by authors outside North

OFFICERS OF THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS, 1957–1958.

Seated, left to right, M. L. Thompson, Editor, *Journal of Paleontology*; R. V. Hollingsworth, President; S. P. Ellison, Jr., Secretary-Treasurer; standing, left to right, J. L. Hough, Editor, *Journal of Sedimentary Petrology*; R. R. Shrock, Past-President; S. A. Levinson, Vice-President.

America. A variety of subjects are treated, but the majority deals with systematic descriptions of fossil animals. Emphasis has been placed upon the descriptive and applied aspects of microfossils—22 of the 29 titles and two-thirds of the total text. Studies are about evenly divided between Paleozoic and post-Paleozoic. The 11 reviews of current literature and 15 notes published averaged 2–3 pages of text.

The State University of Iowa contributed editorial and financial assistance.

2. *Report of the Editor of the Journal of Sedimentary Petrology (Jack L. Hough).*—The *Journal of Sedimentary Petrology* was published in 1956 as Volume 26, Numbers 1 through 4. The total number of pages was 386, or an average of 96.5 pages per number. Nineteen hundred copies of the first number were printed, and twenty-one hundred copies of the last three numbers were printed. During the past 8 years the total cost of printing has increased by approximately 2.5 times; the printing cost per volume has remained nearly constant, at approximately $3.00; and the printing cost per page has decreased to $0.00808, the lowest figure in the history of the Journal. Due to a substantial increase in printing rates, which became effective with the December number of the *Journal*, the *Journal* showed a small net loss after deduction of its share of headquarters office expenses. The *Journal* will show a very substantial loss in 1957 unless the subscription rate and dues are increased.

The contents of Volume 26 include 28 technical articles, 8 notes, 3 discussions, 1 review, 1 page of errata, and 9 pages of index, totalling 301 pages of technical material. Data concerning the Society of Economic Paleontologists and Mineralogists, including the membership list, announcement and program of annual meeting, minutes, and abstracts of papers given at the annual meeting, filled 70 pages.

The distribution of articles, notes, and discussions, according to national origin was as follows: United States, 36; Australia, 1; England, 1; and Switzerland, 1.

The backlog of manuscripts has continued to increase, so that a further increase in size of the *Journal* is desirable. An increase in the subscription rate will be necessary to provide for any expansion.

As in the past seven years, the University of Illinois has provided a part-time editorial assistant.

3. *Report of the Secretary-Treasurer (Samuel P. Ellison, Jr.).*—

MEMBERSHIP, MAILING, AND JOURNAL STATISTICS

	Dec. 31, 1956	*Dec. 31, 1955*	*Dec. 31, 1954*
1. S.E.P.M. Membership:			
Active Members	990	895	751
Associates	292	285	310
Correspondents	5	5	5
Honorary Members	3	3	1
	1,290	1,188	1,067
2. *Journal of Paleontology* Mailing List:			
S.E.P.M. Active & Honorary Members	509	485	434
S.E.P.M. Associates	150	155	165
Subscribers	810	722	684
P.S. Members	624	610	612
	2,093	1,972	1,895
3. *Jour. of Sedimentary Petrology* Mailing List:			
S.E.P.M. Active & Honorary Members	677	607	483
S.E.P.M. Associates	184	171	183
S.E.P.M. Correspondents	5	5	5
S.E.P.M. Subscribers	890	806	740
	1,756	1,584	1,411
4. Edition of *Journal of Paleontology*	2,400	2,200	2,200
5. Edition of *Journal of Sed. Petrology*	2,100	1,900	1,700
6. Number of Pages, *Journal of Paleontology*	1,394	1,084	888
7. Number of Plates, *Journal of Paleontology*	146	108	100
8. Number of Pages, *Journal of Sed. Petrology*	386	317	298
9. New Members	137	161	133
10. Transfers to Active Membership	41	47	44
11. Members and associates dropped for non-payment of dues, 1/1/57	17	16	28

FINANCIAL STATEMENT BY AUTHOR YOUNG & COMPANY

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
BALANCE SHEET, DECEMBER 31, 1956

ASSETS	*Total*	*General Fund*	*Publication Fund*
CURRENT ASSETS:			
Cash	$26,869.14	$19,023.10	$ 7,846.04
Savings account	2,667.49	2,667.49	—
Accounts receivable	826.69	785.94	40.75
Total current assets	*$30,363.32*	*$22,476.53*	$ 7,886.79
PUBLICATIONS:			
Journal of Paleontology:			
Issues prior to 1956—13,310 journals at 50¢ each (2,095 complete volumes)	$ 6,655.00	$ 6,655.00	$ —
Issues 1 to 6 of 1956—963 journals, at cost	2,075.02	2,075.02	—
Reprints in 1948, Volume 1, 1927—706 volumes, at cost	1,539.83	1,539.83	—
Journal of Sedimentary Petrology:			
Issues prior to 1956—2,477 journals at 50¢ each (710 complete volumes)	1,235.50	1,235.50	—
Issues 1 to 4 of 1956—1,345 journals, at cost	1,154.68	1,154.68	—
Special publications:			
Turbidity Currents, 374 issues, at cost	319.81	—	319.81
Recent Marine Sediments, 845 issues, at cost	1,743.66	—	1,743.66
Finding Ancient Shorelines, 481 issues, at cost	840.69	—	840.69
Total publications	$15,564.19	$12,660.03	$ 2,904.16
FURNITURE AND FIXTURES (less reserve, $1,793.84)	$ 1.00	$ 1.00	$ —
DEFERRED CHARGES	$ 1,918.57	$ 277.11	$ 1,641.46
	$47,847.08	$35,414.67	$12,432.41

LIABILITIES AND SURPLUS			
CURRENT LIABILITIES:			
Accounts payable	$ 5,120.27	$ 5,120.27	$ —
Amount payable to Paleontological Society	3,367.79	3,367.79	—
Accrued printer's charges	1,347.30	—	1,347.30
Total current liabilities	$ 9,835.36	$ 8,488.06	$ 1,347.30
DEFERRED CREDITS:			
Subscriptions to journals—net of portion to be received by Paleontological Society	$ 6,921.16	$ 6,921.16	$ —
Subscriptions to special publications	4,968.30	—	4,968.30
Membership dues for 1957 and 1958	6,770.00	6,770.00	—
Total deferred credits	$18,659.46	$13,691.16	$ 4,968.30
SURPLUS, PER ACCOMPANYING STATEMENT	*$19,352.26*	*$13,235.45*	$ 6,116.81
	$47,847.08	$35,414.67	$12,432.41

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

STATEMENT OF INCOME AND SURPLUS
YEAR ENDED DECEMBER 31, 1956

	Total	General Fund	Publication Fund
INCOME:			
Membership dues and subscriptions:			
Journals of Paleontology and Sedimentary Petrology	$ 3,963.00	$ 3,963.00	$ —
Journal of Paleontology	14,204.65	14,204.65	—
Journal of Sedimentary Petrology	7,907.97	7,907.97	—
	$26,075.62	$26,075.62	$ —
Sales of special publications:			
Turbidity Currents	$ 314.55	$ —	$ 314.55
Recent Marine Sediments	1,383.00	—	1,383.00
Finding Ancient Shorelines	3,911.65	—	3,911.65
	$ 5,609.20	$ —	$5,609.20
Sales of back numbers:			
Journal of Paleontology, Volumes 1 to 30	$ 4,309.94	$ 4,309.94	$ —
Journal of Sedimentary Petrology	714.20	714.20	—
	$ 5,024.14	$ 5,024.14	$ —
Sales of plates	$ 417.03	$ 417.03	$ —
Advertising	$ 436.25	$ 436.25	$ —
Convention income	$ 471.77	$ 471.77	$ —
Donation from The American Association of Petroleum Geologists	$ 1,520.00	$ 1,520.00	$ —
Miscellaneous	307.71	307.71	—
	$39,861.72	$34,252.52	$5,609.20
Less: Portion of 1956 income accrued to Paleontological Society	2,825.78	2,825.78	—
	$37,035.94	$31,426.74	$5,609.20
COSTS AND EXPENSES:			
Cost of printing:			
Journal of Paleontology	$13,247.27	$13,247.27	$ —
Journal of Sedimentary Petrology	6,726.47	6,726.47	—
Finding Ancient Shorelines	3,453.52	—	3,453.52
	$23,427.26	$19,973.74	$3,453.52
Expenses:			
Clerical salaries	$ 7,203.75	$ 7,203.75	$ —
Office supplies	588.42	588.42	—
Postage and express	1,855.77	1,743.57	112.20
Office rent	1,500.00	1,500.00	—
Telephone	38.84	38.84	—
Audit fee	200.00	200.00	—
Payroll taxes	148.97	148.97	—
Miscellaneous	1,104.53	866.51	238.02
	$12,640.28	$12,290.06	$ 350.22
Adjustment for increase in inventory of publications	$ (255.31)	$ (199.89)	$ (55.42)
	$35,812.23	$32,063.91	$3,748.32
NET INCOME (LOSS)	$ 1,223.71	$ (637.17)	$1,860.88
SURPLUS AT DECEMBER 31, 1955	18,128.55	13,872.62	4,255.93
SURPLUS AT DECEMBER 31, 1956	$19,352.26	$13,235.45	$6,116.81

4. *Report of the Research Committee (Curt Teichert, Chairman).*—Between April, 1956, and April, 1957, the membership of this committee was as follows: O. L. Bandy, V. E. Barnes, W. C. Bell, R. V. Hollingsworth, D. L. Inman, S. A. Levinson, A. R. Loeblich, H. H. Murray, R. H. Nanz, W. J. Plumley, R. R. Shrock, R. A. Siever, L. L. Sloss, F. B. Van Houten, and Curt Teichert.

At the annual meeting in 1955 the council accepted a proposal from the committee to direct the chairman to organize a symposium on biostratigraphy to be held at the 1957 meeting. The response to the plan of the symposium was good and the number of papers offered exceeded the number that could be accepted. In the selection of papers preference was given to contributions demonstrating applicability of study of evolutionary lineages to biostratigraphy and usefulness of planktonic faunas in correlation. Authors of papers were V. Standish Mallory and H. E. Wheeler, Christina L. Balk and J. L. Wilson, T. A. Amsden, M. K. Elias, D. A. Myers, W. C. Hoffmeister and L. R. Wilson, A. R. Loeblich and Helen Tappan. Fossil groups discussed included foraminifera, bryozoa, trilobites, and plant microfossils, and ranged in age from Cambrian to Eocene.

The Research Committee recommended the following persons as recipients for the Best Paper Awards: W. R. Walton for the award for the best paper in the *Journal of Paleontology* for 1955 for the paper entitled, "Ecology of Living Benthonic Foraminifera, Todos Santos Bay, Baja California," and Louis F. Dellwig for the award for the best paper in the *Journal of Sedimentary Petrology* for 1955 for the paper entitled, "Origin of the Salina Salt of Michigan." The recipients of the awards were presented to the president, R. R. Shrock, by Curt Teichert at the joint session of A.A.P.G. and S.E.P.M at St. Louis.

The Research Committee presented to the council by unanimous vote the nomination of Henry V. Howe as an Honorary Member of the Society. The council approved and the presentation was made at the annual meeting by Marcus A. Hanna. The Committee also presented to the council by unanimous vote the nomination of Philip H. Kuenen as Correspondent of the Society. The council approved and presentation was made by R. R. Shrock at the annual meeting.

The Research Committee held a meeting at St. Louis on April 1, 1957, at 10:30 A.M. Those present were: W. C. Bell, R. A. Siever, W. J. Plumley, L. L. Sloss, R. R. Shrock, R. V. Hollingsworth, Stuart A. Levinson, A. R. Loeblich, Haydn H. Murray, H. A. Ireland, Grover Murray, W. A. Akers, and W. D. Pye. The Committee adopted a resolution to recommend to the council that authors of symposia papers should be requested to present final publishable manuscripts of their papers on September 15 of the year in which the symposium is held.

The Committee selected "Silica in Sediments" as the topic for the Research Committee Symposium in 1958. For 1959 it was decided to organize a symposium on the general subject of "Classification of Sedimentary Units," the exact title to be chosen by the chairman of that symposium in consultation with the Research Committee.

5. *Report on the Earth Sciences Division of the National Research Council (Francis J. Pettijohn, S.E.P.M. Representative).*—The Division operates primarily through its various advisory and technical committees. The activities of several of these are of special interest to the members of S.E.P.M. The Division either directly (by special committees) or indirectly (by nominating panels from which National Science Foundation committees are appointed) plays an important role in furthering graduate education in geology, mineralogy and paleontology.

The technical committees of the Division are many and varied. Of these the Committee on Clay Minerals and the Committee on a Treatise on Marine Ecology and Paleoecology are perhaps of the greatest interest to members of S.E.P.M. The former, established in 1953, has organized a series of Clay Minerals Conferences, the results of which have been or are being published. The fifth Conference was held at the University of Illinois in October, 1956. The *Proceedings* of the various conferences are published and distributed by the National Research Council. Dr. Ada Swineford, of the Kansas Geological Survey and member of S.E.P.M., has been named Editor for the *Proceedings* series.

The Committee on a Treatise on Marine

Ecology and Paleoecology has completed its work. The two-volume *Treatise* is in process of publication. Both volumes will appear as a *Memoir* of the Geological Society of America.

6. *Report on the American Geological Institute* (*Francis J. Pettijohn*).—Inasmuch as *Geotimes* is now sent to most North American geologists, including all members of S.E.P.M., it seems unnecessary to report in detail the activities and projects of the American Geological Institute regularly reviewed in *Geotimes*.

Your representatives attended the meeting of the Board of Directors of A.G.I. in Minneapolis, November 2, 1956. The meeting was devoted to the usual reports of officers and committees. The principal item of interest was the report of progress made toward placing the Institute on a better financial footing and the report on the transformation of the old *Newsletter* into *Geotimes*.

Member society support has generally been revised upwards. The Geological Society of America and the American Association of Petroleum Geologists both made substantial increases in their support of the Institute. The Mineralogical Society and the Association of Geology Teachers agreed to contribute an amount equal to 10 per cent of their dues. The council of your Society, because of its status as a Technical Division of A.A.P.G., voted to contribute a per capita assessment for its Associates (most of whom are not members of the A.A.P.G.) equal to the per capita contribution made by the Members by virtue of their membership in the parent society.

According to our By-Laws, S.E.P.M. has two members on the Board of Directors of the American Geological Institute, namely its President and Past-President. The terms of the Directors are, therefore, two years beginning with the Annual Meeting of the Society in late March or early April. But the Institute Board operates on a two-year basis beginning and ending in November—the time when the Institute has its Annual Meeting. Your representatives suggest that some effort be made to bring the terms of service of its directors into better agreement with the A.G.I. operating year.

7. *Report of the S.E.P.M. Representative to the A.G.I. Government Relations Committee* (*Norman S. Hinchey*).—The A.G.I. Government Relations Committee met on April 23 and November 1, 1956. On March 31, 1957, the Committee met jointly with the A.A.P.G. National Responsibilities Committee. Among matters which were considered by the Committee at its meetings were the following topics of interest:

(1) Reports on pertinent activities of the Scientific Manpower Commission were made by Dr. Howard A. Meyerhoff. It was the feeling of the group that the profession was not always well informed on Selective Service matters which concern its members. The Committee moved to explore the possibility and desirability of a periodic summary statement of the military draft situation, such a statement to be distributed to A.G.I. members or perhaps published in *Geotimes*.

(2) Apparently, a recent report by the Bureau of Labor Statistics for the National Science Foundation does not classify exploration in geology as research. As a result the B.L.S. report states that only seven per cent of geologists are engaged in research, a smaller percentage than in any other scientific field. Complaints concerning this action were made by the A.G.I. and S.M.C. to the B.L.S, which agreed to make some changes. It was recommended by the Committee to the Board of Directors of A.G.I. that an *ad hoc* committee, under the purview of the Executive Committee of A.G.I., be established to form definitions of the terms research, development, and exploration as these terms are used in earth science and as they should be used.

(3) There was discussion of the Department of the Interior's comprehensive plan to expand and improve the national parks and monuments, a plan known as "Mission 66." It was voted to recommend to the A.G.I. Directors that a committee be appointed to learn the details of the plan and to offer A.G.I. cooperation in developing its geological aspects. An ultimate hope is that more and better geological information concerning the parks and monuments be presented to the public.

(4) The committee requested the Scientific Manpower Commision to collect and supply facts on the growth of government research and its effect upon the scientific manpower pool and its utilization.

(5) Ways and means of promoting in-

terest in geological instruction at the U. S. Military Academies were considered, and it was suggested that the possibilities be explored with the office of the Chief of Engineers.

(6) Regretting the fact that essential geological advice is seldom used in the planning of public works, the Committee decided that the situation calls for action and appropriate steps to correct the situation will be considered at future meetings.

(7) The meeting of March 31, 1957, was a joint meeting with the A.A.P.G. National Responsibilities Committee. The current work of each of the committees was considered. The question was posed as to whether or not there might be unnecessary overlap or duplication of effort by each of the committees when they were obviously concerned with some of the same problems. After some discussion, it was agreed that it would be desirable for both of the committees to continue to operate as they are now operating. It was generally felt that any overlapping or duplication of activities would be desirable and that each of the committees might be strengthening the efforts of the other.

8. *Report of the Joint Committee on Invertebrate Paleontology* (*Raymond C. Moore*). —The project to produce a modern comprehensive textbook on invertebrate fossils by the cooperative effort of selected specialists orginated from a proposal made by B. F. Howell, of Princeton University, approximately 10 years ago. This stemmed from the evident need then existing for an up-to-date volume comparable to the Zittel-Eastman text on invertebrate paleontology published in 1900 and subsequently issued as a revised edition in 1913. The Paleontological Society is the organization that received Howell's suggestion and disposed of it by appointing him chairman of a committee to find someone bold or witless enough to accept the responsibility of trying to accomplish the objective. As a former editor of the *Journal of Paleontology*, I was approached by the committee with invitation to plan a work program and direct its operation. I responded by saying that if the Paleontological Society and Society of Economic Paleontologists and Mineralogists jointly accepted sponsorship of the project and agreed on naming me to undertake it, I would do my best to carry it forward. The societies approved a proposal to establish a Joint Committee on Invertebrate Paleontology under my chairmanship for the purpose of developing definite plans. Meanwhile, before this committee actually was appointed, the desirability of including the Palaeontographical Society as partner in the enterprise seemed clear, because participation by this society, founded more than a century ago, would bring British support and link together the leading organizations of English-speaking paleontologists. The Palaeontographical Society in 1948 agreed to be a co-sponsor of what by then was designated as a "Treatise on Invertebrate Paleontology." Accordingly, the joint committee was set up, with ten members from the Paleontological Society, ten members from the Society of Economic Paleontologists and Mineralogists, and ten members from the Palaeontographical Society.

The first task was to plan the scope of intended text and illustrations, and to prepare a schedule of author assignments. Next there were decisions to make about innumerable features of style. How could reasonable unity be attained in materials prepared by dozens of different workers working in widely scattered parts of the world? Most of all, where was money to pay costs of making needed illustrations and other items of expense? The sponsoring paleontological societies had not agreed to supply any funds and obviously their resources would be quite inadequate for payment of any considerable costs. At this stage the Geological Society of America was approached and must be credited for financial underwriting of the *Treatise* effort. Without this support we could have accomplished little. Counting direct and indirect appropriations made by the Geological Society for preparation of *Treatise* materials (not including publication costs), more than $40,000 has been furnished from 1948 to 1957. Also, as regards publication, account should be taken of the fact that all composition of type and printing work done by the University of Kansas Press for volumes of the *Treatise* has been undertaken without charge of a single dollar of profit to the Press. Thus, the sale price of published volumes is very much less than

otherwise would be possible.

To date, 7 of the 22 scheduled parts of the *Treatise* (excluding general Introduction and consolidated Index) have been published. These represent a total of 1,958 pages of text and illustrations, the latter containing more than 11,000 individual figures. The most recently issued part is the volume on Ammonoidea, distribution of which began in March, 1957; this constitutes a truly unique book in that in addition to authoritative description and illustration of morphological features of these fossils, it contains diagnoses and figures of virtually all known genera in the world recognized as valid, accompanied by notation of type species and all synonyms. The authors are four American and four British paleontologists who include outstanding leaders in study of the groups treated. Volumes such as this one serve to establish the *Treatise* as the most complete and authoritative text in the world concerning invertebrate fossils. This Society and the others that are sponsors of the *Treatise* have reason to take great pride in the publication of the volume on Ammonoidea.

Work is proceeding at varied pace on the yet unpublished parts of the *Treatise*, those farthest advanced being Part O on trilobitomorphs, Part Q on ostracodes, Part I on chitons, scaphopods and some gastropods, Part W on conodonts, worms and problematica, and Part C on foraminifers. These will go to press as rapidly as they can be made ready. A lull in appearance of Treatise volumes now must be anticipated because of the processing time required after materials are ready for the press. Experience shows that this amounts to about six months for small units and as much as eleven months for large ones.

9. *Report of Representative to Second Nuclear Engineering and Science Conference* (*Roland F. Beers*).—The second Nuclear Engineering and Science Conference was held in Philadelphia on March 11 to 14, 1957. Together with three related programs running the same week, the Conference is also known as the 1957 Nuclear Congress. The Congress was sponsored by 24 national and international organizations, including the American Geological Institute, to which the Society of Economic Paleontologists and Mineralogists appointed your reporter as a delegate. Professor Paul F. Kerr served as Chairman of the A.G.I. program, and W. R. Thurston as Executive Secretary. The papers presented by the A.G.I. members were coordinated by Professor Kerr's committee through the office of Mr. Thurston at the National Academy of Science-National Research Council, following preparation of a list of invited papers by the A.G.I. committee. The entire Congress program was coordinated by the Engineers Joint Council of New York.

The technical program consisted of 33 separate sessions from Monday through Thursday, and in addition, 4 other technical sessions or addresses at luncheon or dinner meetings. Topics covered in these sessions are as follows: Plant Containment Concepts and Design, Fuel Cycles—Fuel Production and Recovery, Protection of Water Supplies, Educational Use of Reactors, Waste Disposal, Merchant Ship Safety; Reactor Operation and Maintenance, Standardization in the Nuclear Field, Primary Coolant Systems, Plant Components, New Limits and Codes for Radiation Protection, Shielding-Structural Protection and Control of Fission Products, Radiation Processing, Reactor Design, Uranium Metallurgy and Radiation Effects, Reactor Plant Instrumentation, Reactor Control and Simulators, Natural Resources, Metallurgy of Reactor Materials, Heat Transfer and Heat Evolution, Problems Related to Heat Transfer, Metallurgy of Uranium-Zirconium and Uranium-Niobium Alloys, and Reactor Instrumentation Development.

Separate sessions were held on Thursday and Friday covering "Hot" Laboratories and the 5th Atomic Energy in Industry Conference. Preprints of many of the technical papers were available at the office of the American Society of Mechanical Engineers at 30¢ each prior to the meetings. The program contains a list of the titles and authors of available papers and orders may be placed with A.S.M.E.

10. *Report of Pacific Coast Section* (*J. D. Bainton*).—The Pacific Section has an active paid up membership of 161 and a balance in the treasury of $1,873.90.

This year, S.E.P.M. membership awards were granted by the Pacific Section to 16

students from various Pacific Coast Colleges and Universities. The faculty of the Geology or Paleontology Department of each school nominated the student to receive this award, which included subscriptions to both Journals. This project was voted on and established by the members at the annual meeting in Los Angeles in November, 1956.

The monthly Biostratigraphy Seminar, which is sponsored jointly by the Pacific Section S.E.P.M. and the Bakersfield Evening School, is again in progress. Eight papers by research workers from West Coast schools, covering the fields of stratigraphy, paleontology, and ecology, are on this year's program. Edwin H. Stinemeyer is chairman, and the average attendance at the meetings is approximately 40.

The S.E.P.M. Pacific Section will sponsor their annual dinner meeting and field trip this year on May 17th and 18th. Dr. Francis P. Shepard is chairman of the event and E. Dean Milow and R. R. Lankford are co-chairmen. The paleontology, stratigraphy, and sedimentation of the cliff exposures, in the vicinity of Scripps Institution of Oceanography and the Torrey Pines area, will be studied and sampled. Mr. Milow will present a paper on the Stratigraphy and Paleoecology—La Jolla Area at the Friday evening dinner preceding the trip.

The Pacific Section S.E.P.M. will again cooperate with the A.A.P.G. and S.E.G. in putting on the Annual Fall Meetings at Los Angeles on November 7th and 8th. A half-day technical session and dinner meeting are being planned by Dr. E. L. Winterer, program chairman.

A dinner dance was held in December which was co-sponsored by the S.E.P.M.-A.A.P.G.-S.E.G.

11. *Report of Gulf Coast Section (Lloyd M. Pyeatt).*—The 1956 annual meeting of the Section was held in San Antonio, Texas, October 31-November 2. The first day of the two days of Technical Sessions was a joint meeting with the Gulf Coast Association of Geological Societies. The second day the Gulf Coast Section held its own sessions concurrently with the other meeting. Papers were presented by Section members at each of the sessions.

The Annual Business Meeting was held on November 2nd in San Antonio at the close of the Technical Sessions, with President E. H. Rainwater presiding. Following the reports from the Secretary, Treasurer, and Committee Chairmen, there was a discussion of projects which the Section is undertaking. The meeting was then turned over to the new president, Lloyd M. Pyeatt.

Two field trips in the Gulf Coast during 1956 were sponsored by the Gulf Coast Section. On May 3, 4, and 5 a large group of geologists was shown the famous Miocene localities of western Florida by Messrs. Harbans S. Puri and Robert O. Vernon. A guidebook entitled, "A Summary of the Geology of Florida with Emphasis on the Miocene Deposits, and a Guide to the Miocene Exposures," was prepared by the Florida Geological Survey, Dr. Herman Gunter, Director. This publication may be purchased from the Florida Geological Survey, Tallahassee.

On November 3, the day following the annual meeting of the Section, a field trip was conducted especially for the Gulf Coast Section by Robert Pavlovic, Fred L. Stricklin, Jr., Keith P. Young, and Kenneth J. DeCook. Dr. John R. Sandidge was chairman of the committee which planned and conducted the trip into the classic Lower Cretaceous area between San Antonio and Austin, Texas, and prepared a guidebook entitled, "Guidebook, Lower Cretaceous Field Trip, November 3, 1956," which can be obtained from the South Texas Geological Society, San Antonio.

12. *Report of Permian Basin Section (Hugh N. Frenzel).*—The Permian Basin Section has completed its third year of activities and the first full year of operation under its constitution. During this first year the constitution was amended to require that officers of the Permian Basin Section be members of the national S.E.P.M.

P.B.S. membership stands at 270 which is comparable with previous years despite the fact that 40–50 new members have been added each year. Society funds total $1,041.75. It is believed that sale of publications will tend to increase this fund. The Executive Committee decided to use surplus funds to conduct "Little Distinguished Lecture Tours" of outstanding speakers to several of the Permian basin towns.

Activities during the year included the

first annual meeting held in Fort Worth, Texas, May 11, 1956. Meeting attendance was about 80. A technical session was held with seven papers being given. On May 12th a field trip was held to study the "Nill Creek Beds of the Lower Strawn of Parker County." P.B.S. members in Fort Worth under the leadership of Wendell J. Stewart, Gregory Turner, Donald Zimmerman and Leo Hendricks organized the meeting and field trip. The 1956 officers taking over at the close of the meeting were: Hugh N. Frenzel, President; W. Frank Dameron, 1st Vice-President; Frank B. Conselman, 2nd Vice-President; Tom Schneider, Secretary; and Ed A. Vogler, Treasurer.

The second annual meeting was held in Lubbock, Texas, March 15 and 16, 1957. Meeting attendance was 160. Twelve papers were given during the technical sessions. The P.B.S. student chapter at Texas Technological College was host society and the meeting was organized under the leadership of John P. Brand, Granville Waters, F. A. Wade, and Frank B. Conselman. The 1957 officers taking over at the close of the meeting were: W. A. Waldschmidt, President; W. W. Roye, 1st Vice-President; Donald A. Zimmerman, 2nd Vice-President; M. R. Stipp, Secretary; and Booker L. McDearmon, Treasurer.

A two day field trip will be held April 26 and 27, 1957, to study the Wolfcamp rocks of the Glass Mountains.

13. *S.E.P.M. President's Report (Robert R. Shrock).*—Finances remain our Society's most serious problem. The General Fund showed a *loss* of $637.17 in 1956 as compared with a profit of $5,362.37 for 1955. This loss is partially due to increased printing costs. The Publication Fund showed a *profit* of $1,860.88 in comparison with a profit of $2,502.74 for 1955. Thus the over-all profit for the year 1956 amounted to $1,223.71, but part of this amount represents inventory. It should be pointed out that in 1957 printing costs will be substantially increased, and it is largely because of this increase that the council has voted to amend the by-laws so as to provide for the increase in dues subsequently approved in the Business Meeting.

Successive increases in printing costs are becoming more and more of a problem for a Society like ours, with a relatively small membership (1300+) and two journals, one of which, the *Journal of Paleontology*, is abnormally expensive because of the large number of costly illustrations. The Paleontological Society, with which we have an arrangement for publishing the *Journal of Paleontology*, is struggling with this same problem, and their President, G. A. Cooper, has appointed a special committee "to study the future of the *Journal*."

Our journals represent the most important activity of our Society, and its chief reason for existence, and ways will have to be found to meet the rising costs of printing, or the size and number of issues will have to be drastically reduced—an action which would be disastrous to the future growth of our Society. The modest increase in dues, and in the subscription rate to non-members for the *Journal of Sedimentary Petrology*, approved for next year will help to some extent in meeting future increases in printing costs, but other income will have to be found if our journals are to flourish and meet the future demands on them.

Quite a different problem, and one which is highly encouraging, is the underwriting of special publications, symposia, and the like that have a good chance of being self-liquidating. These special publications are not only highly desirable for members of our Society; they help to replenish the Publication Fund and hence make possible publication of new items.

A special committee, composed of Stuart A. Levinson (Chairman), A. R. Loeblich, Jr., and W. C. Bell, was appointed last year and charged with studying the whole problem of publication policy. Their excellent report was submitted to the council at the annual meeting in St. Louis and becomes the starting point for positive future action.

This year will see the appearance of Special Publication No. 5 on *Regional Aspects of Carbonate Deposition*, the results of a symposium held here in St. Louis in 1954. As of March 1, 1957, 1,585 of the first edition of 2,500 (increased from 2,000 because of the heavy prepublication ordering) had been sold by prepublication orders, and there is every indication that this symposial report will be out of print in a very short time.

Our membership grew vigorously through

the year, as shown in the following tabulation:

	March, 1956	*March, 1957*	*Increase*
Members.....	900	994	94, 10.4%
Associates.....	280	305	25, 8.9%
Correspondents.	5	6	1, 20 %
Honorary Members.....	3	3	0, —
	1,188	1,308	120, 10+%

Nevertheless, our total membership is far below what it should be to support our program of activities. Our Technical Program is becoming an increasingly more important part of the annual joint meeting with the A.A.P.G. At New York, in 1955, 40 papers were presented on the S.E.P.M. program as compared with 62 on the A.A.P.G. program. In Chicago, last year, 42 papers (including those in two symposia) were presented in the S.E.P.M. program as compared with 31 on the A.A.P.G. program! At the 1957 meeting in St. Louis, our Society will present 47% of the papers on the Technical Program (25 papers by S.E.P.M. compared with 28 papers by A.A.P.G.). Clearly this growing importance of our Society must be further increased by the concerted effort of all members to get new members, particularly from the growing number of students and recent graduates, and from younger men offering papers on our technical program.

We regret that W. M. Furnish finds it necessary to resign editorship of the *Journal of Paleontology* at the end of his present term, as his efficient service has been much appreciated. Fortunately, we shall have the editorial services of M. L. Thompson for the coming year, and I wish to express for the Society our gratitude to Dr. Thompson for accepting the heavy and important responsibility of Editor. Our editors are our most important officers in that they are directly responsible for the nature and quality of our two journals. Accordingly, we also record our gratitude to J. L. Hough for his usual efficient handling of the *Journal of Sedimentary Petrology*, and we are pleased to know that he will continue as editor next year.

In order to conform with action taken by the Executive Committee of the A.A.P.G., the S.E.P.M. will henceforth make an annual contribution to the A.G.I. that will be determined by the number of associate members as of December 31 of each year. The amount that will be contributed in 1957 will be approximately $216.

Selection of candidates for our presidents and vice-presidents has been of growing concern to some of us who have been more closely associated with administrative affairs of the Society than is the general membership. Last year a special committee was appointed to study this problem and to suggest constructive action. This committee, consisting of Stuart A. Levinson (chairman), W. C. Krumbein, and Grover Murray, made its report to council at the April, 1956, meeting in Chicago, and recommended the following: (1) that the two nominating committees be appointed from the membership-at-large; and not an Eastern and Western Committee, and that on each nominating committee there be wide geographic distribution of members; and (2) that the activities of the Research Committee be directed by a chairman and a vice-chairman, to be appointed by the president, with approval of the council, from the active members of the committee and that the term of office of the chairman shall be one year. Approval was given to these recommendations, and they were put into effect immediately.

The Research Committee performs some of the most important functions of our Society; hence its guidance and membership should be a prime concern not only of the council but also of the membership-at-large. The importance of recent symposia organized by this committee has raised the question of how best such symposia can be planned well in advance and their papers published with maximum speed. A special committee recommended to council, and council approved, that Research Committee symposia be determined two years in advance and that the ultimate chairman of the symposium be appointed vice-chairman two years in advance so as to have adequate time to organize the symposium. It is hoped that this procedure will make it possible to have all manuscripts in hand at the time of the meeting, or within a few months thereafter, so that publication, if approved by the Standing Committee on Publications and by council, can follow promptly.

The S.E.P.M. became affiliated with the

American Association for the Advancement of Science following council approval of the recommendation of a special committee set up last year by President Pettijohn, to investigate and report on the matter. This committee, consisting of Chalmer L. Cooper (chairman), J. Marvin Weller, and H. N. Frenzel, reporting to council at the April, 1956, meeting in Chicago, recommended affiliation, and the council approved. Subsequently, appropriate action was taken, and the Society was notified that its request for affiliation had been approved on December 27, 1956. Messrs. Verner Jones and George Wilson were appointed to serve as S.E.P.M. representatives to the A.A.A.S. Council.

During the last year, our representative on the Advisory Committee on Radioactive Mineral Exploration, Harold N. Fisk, informed me that it had been unanimously recommended that the committee be dissolved as it felt that the original objectives of the committee had been accomplished. These objectives were to encourage and urge companies exploring for oil and/or gas to combine with such exploration the search for radioactive minerals, and to advise those interested as to prospective areas, methods of exploration, and sources of information. Fisk reported that in the four years since the committee was first organized, many oil companies have made the search for uranium part of their program in exploration and the committee felt that its efforts had been adequately rewarded.

A special committee was appointed to study and report on the question: How many copies of our two journals should be published in the future? This committee, consisting of H. B. Stenzel (chairman), J. L. Hough, W. M. Furnish, W. C. Krumbein, and William Evitt (for the Paleontological Society), was to report to council at the 1957 annual meeting, but, unfortunately, no report was submitted because of the chairman's illness. In connection with the work of this committee, H. B. Stenzel was appointed by council to be the S.E.P.M. representative on the Joint Committee with the A.A.P.G. to study reprinting back issues of S.E.P.M. publications.

Services were given during the year by the following, to whom I extend my sincerest gratitude: (1) two nominating committees consisting respectively of H. N. Fisk (chairman), L. M. Cline, and S. G. Wissler. and H. S. Ladd (chairman), B. Kummel, and F. B. Phleger; (2) Daniel A. Busch as Vice-Chairman, Presiding Officer for S.E.P.M., and member of the Steering Committee for the 1957 joint annual meetings in St. Louis; (3) Curt Teichert and Alfred R. Loeblich as chairman and vice-chairman, respectively of the Research Committee and also as organizers of the Symposium on Biostratigraphy, and V. E. Barnes, R. V. Hollingsworth, D. L. Inman, Stuart A. Levinson, and Haydn Murray as members; (4) W. J. Plumley as chairman of the Symposium on Geochemistry at the St. Louis meeting; (5) Hans Thalmann as official representative and Grover E. Murray as a professional delegate to the XXth International Geological Congress at Mexico City last summer; (6) R. C. Moore as S.E.P.M. representative on the committee for preparation of the *Treatise on Invertebrate Paleontology;* (7) Jules Braunstein as S.E.P.M. representative on the A.G.I. Glossary Committee, whose *A Glossary of Geology* is now in press and will be issued as a publication of the American Geological Institute; (8) the various chairmen and co-chairmen of the technical sessions of the annual meeting, particularly Vice-President R. V. Hollingsworth, who had the primary responsibility for the St. Louis Technical Program; (9) Samuel P. Ellison as chairman of the Resolutions Committee for the annual meeting; and finally (10) Robert H. Dott, and his efficient secretary, Mrs. Ruth Tener, for valuable advice and assistance on many matters.

It was moved, seconded, and carried that the above reports be approved and that they be published in the Society's publications.

The following change in the S.E.P.M. By-Laws was presented to the business meeting (brackets indicating deletions, italics indicating additions):

ARTICLE I. DUES

2. The annual dues of members and associates of the Society who desire only the *Journal of Paleontology* shall be [eight dollars ($8.00)] *ten dollars ($10.00)*. The annual dues of members and associates who desire only the *Journal of Sedimentary Petrology* shall be [five dollars ($5.00)] *seven dollars ($7.00)*. Members and associates may receive both Journals by the payment of [thirteen dollars

($13.00)] *seventeen dollars* (*$17.00*). Members of the Society who are also members of the Paleontological Society and receive the *Journal of Paleontology* through the latter Society, may retain membership in the Society of Economic Paleontologists and Mineralogists by the payment of [one dollar ($1.00)] *two dollars* (*$2.00*) per year dues. . . .

The foregoing change was approved by a unanimous vote, the change in the *Journal of Paleontology* dues and the Joint Society dues being contingent upon similar action by the Paleontological Society.

The meeting was turned over to incoming President R. V. Hollingsworth.

The Resolutions Committee, composed of Samuel P. Ellison, Jr. (chairman), J. L. Hough, and Stuart A. Levinson, presented the following "Resolutions of Thanks."

BE IT RESOLVED THAT in behalf of the Society we extend an expression of our sincere thanks to the following:

TO R. V. HOLLINGSWORTH, chairman, and the members of the S.E.P.M. Technical Program Committee and to the speakers for the high quality of papers on the 1957 program;

TO DANIEL A. BUSCH, general chairman of the S.E.P.M. convention, for his capable handling of the details of the meeting;

TO CURT TEICHERT, chairman of the Research Committee, and A. R. LOEBLICH, JR., vice-chairman, for the excellent research symposium on Biostratigraphy;

TO SHEPARD W. LOWMAN, for arranging the papers on Paleontology and Stratigraphy;

TO SHERMAN A. WENGERD, for preparation of that part of the program dealing with Sedimentary Mineralogy, Petrology, and Sedimentology;

TO WILLIAM J. PLUMLEY and HEINZ A. LOWENSTAM, for arranging the papers on Geochemistry of Sedimentary Materials;

TO RUFUS LEBLANC, for editing our special publication, *Regional Aspects of Carbonate Deposition;*

TO HAROLD T. MORLEY, general chairman of the convention, and to the chairmen and members of all the convention sub-committees, for their efforts in the organization of the St. Louis meeting;

TO THE EXECUTIVE COMMITTEE of the A.A.P.G. for appropriating $1,500.00 as office rent for the Society Headquarters at Tulsa and for allowing the Society to share in the net income from the 1956 Chicago Convention:

TO ROBERT H. DOTT, for his valuable service to the Society as its Business Manager;

TO OUR EDITORS, W. M. FURNISH and JACK L. HOUGH, for their untiring efforts in behalf of the *Journal of Paleontology* and the *Journal of Sedimentary Petrology;*

TO THE JEFFERSON HOTEL, for providing excellent convention headquarters facilities;

AND TO THE CITY OF ST. LOUIS, for the use of the Kiel Auditorium and for full cooperation at all times.

It was moved, seconded, and carried that the above Resolutions be adopted.

Before adjournment at 6:00 P.M. Past-President Shrock read a SPECIAL RESOLUTION on the death of WILLIAM HENRY TWENHOFEL: this is printed as a memorial on a foregoing page of this number of the *Journal.*

SPECIAL NOTICE

The 1957 S.E.P.M. and A.A.P.G. program, containing abstracts of papers presented at the St. Louis Meeting, will be mailed free, on request, to anyone desiring a copy. Orders should be sent to: S.E.P.M. Headquarters, Box 979, Tulsa 1, Oklahoma.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 27, NO. 2, P. 223
JUNE, 1957

ANNOUNCEMENTS

S.E.P.M. PROGRAM FOR LOS ANGELES

MARCH 10–13, 1958

The A.A.P.G.-S.E.P.M. annual meeting for 1958 will be held in Los Angeles, March 10–13. All members of the Society are invited to submit papers for the program; papers from non-members are also solicited; however, non-members are required to have a member sponsor the paper. Persons submitting papers should send them directly to the appropriate program chairman.

W. H. Akers, Chairman Paleontology and Stratigraphy
The California Company
The California Company Building
New Orleans, Louisiana

C. M. Gilbert, Chairman Mineralogy and Sedimentary-Petrology
University of California
Berkeley, California

H. A. Ireland, Chairman Research Committee
University of Kansas
Lawrence, Kansas

The program is rapidly becoming full and it is suggested that if you desire to present a paper during this meeting that you notify the program chairman as soon as possible. November 1 is the deadline for submitting abstracts of papers presented during the technical programs and the symposium.

Silica in Sediments has been selected as the subject for the symposium for the Los Angeles meeting. The papers will be selected or requested according to a specific framework set up by the Research Committee. It is expected that the seven papers which will make up this symposium will be scheduled before June 1; however, if arrangements are delayed, an additional paper concerning some important aspect of silica in sediments may be included, if sent to the chairman of the Research Committee at once.

At the 1957 annual meeting, the council of the S.E.P.M. voted to inaugurate a "Best Paper Presented at the Annual Meeting Award." The best paper will be selected from the 1958 S.E.P.M. program and the award will be presented to the recipient at the business meeting the following year. The basis for selection will be (1) content, (2) organization, (3) quality of slides, and (4) presentation.

Plans are moving along at a rapid pace, and the indications are that we have a great convention in the making. We hope that you will take part in our program by presenting a stimulating and timely paper.

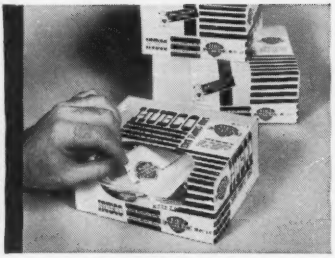
STUART A. LEVINSON
Vice-President S.E.P.M.
Chairman, Technical Program

GULF COAST ASSOCIATION OF GEOLOGICAL SOCIETIES

NOVEMBER 6–8, 1957

The Gulf Coast Association of Geological Societies will hold its 7th Annual Convention November 6–8, 1957, at the Roosevelt Hotel, New Oreleans, Louisiana.

NEW HUBCO HANDY PACK



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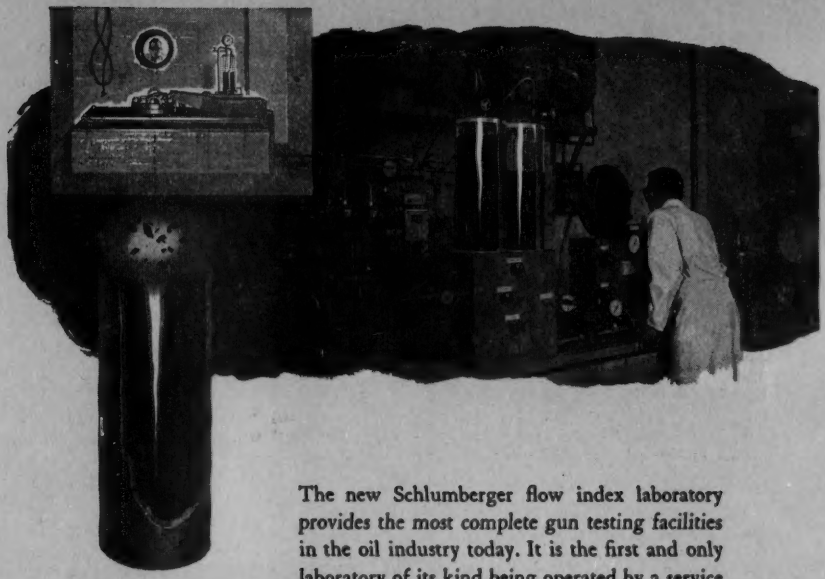

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